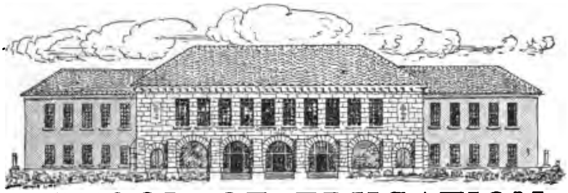
STUDENT'S MANUAL OF PHYSICS

LEROY C. COOLEY



Fernando Sanford,

PHYSICS

THE STUDENT'S MANUAL

FOR THE

STUDY ROOM AND LABORATORY

BY

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COOLEY'S PHYSICS

W. P. 3

PREFACE.

THE best method of teaching physics to beginners consists of a wise combination of oral instruction, the study of a text-book, and laboratory work. By oral instruction, involving illustrative experiments, the pupil should be enabled to see, in the outset, just what phenomena are to be the subject of each study. In the text-book he should find a plain, logical, and accurate outline of the facts and explanations, with formulated statements of definitions and principles relating to the subject. In the laboratory he should practice those experimental methods of reaching or testing truths which will most surely impel him to be circumspect, methodical, accurate, and conscientious in whatever he does and thinks. An outline of such a course is presented in this book.

This work differs from many other elementary text-books in this respect: It contains much less descriptive material for purely illustrative work, and much more of that which is necessary for systematic and successful quantitative study.

The kind and quantity of illustrative work in the class room would better be left to the judgment of the teacher than to be fully laid down in the text-book. The teacher can better adapt it to the age and attainments of his pupils, and should be free to carry it out with the apparatus which he may possess. Such adaptation, together with the charm of novelty, will make the phenomena real and attractive in a degree far beyond the power of any printed description. Moreover, so much illustrative material is already accessible to both teacher and pupil

that it need not be republished, and its omission from the text-book leaves room for the discussion of important facts and for the directions which are indispensable for quantitative study in the laboratory.

A laboratory course accompanies the text throughout this book. The experiments are described at the close of the numbered sections and are set in different type. By this artifice they practically leave the continuity of principles unbroken. They may be modified for use, or omitted, and yet leave the general course intact. But their presence in the book will encourage the introduction of the laboratory method into schools which have not adopted it, by exhibiting a definite course, which is adapted both to the subjects treated and to the powers of the student, and which can be introduced with comparatively small expense. Especial care has been taken to select experiments which will not overtax the abilities of beginners nor require expensive apparatus, but which call for thoughtful work and lead to accurate results.

Among other features of the text designed to be prominent throughout the book are the following:

The discussions flow smoothly from point to point in the order of their dependence, instead of passing abruptly from one to another without scrupulous regard to their mutual relations. An abrupt, fragmentary, or telegraphic style is not conducive to an easy and complete mastery of any subject.

A notation to designate the subdivisions of subjects has been adopted which leaves the continuity of the treatment unbroken, and at the same time individualizes every distinct feature, and renders future reference to it easy.

By means of cross references, and the systematic notation, the student is directed to the facts and principles which have been already studied and are involved in the study of the subject in hand. By this means a constant review of fundamental points may be kept up.

Arbitrary statements of definitions and principles have been avoided as far as practicable. Terms are introduced as names to designate ideas which have arisen, and the formal definitions and statements of laws are intended to be summaries of the characteristics of the phenomena which they describe.

In the interest of clear thinking and accurate expression of thought, a serious attempt has been made to impart clear-cut conceptions of physical quantities, and to protect the pupil from the pernicious influence of ambiguous terms. For example, there will be found a persistent use of the word "mass," whenever quantity of matter is the idea to be expressed, while the word "weight" is used to designate the attraction between bodies and the earth, and for no other purpose. In like manner the word "force" is used simply to designate the mutual action of bodies by which changes are produced.

It has not been forgotten that the teaching of physics in secondary schools is chiefly to pupils who will complete their school studies in these institutions. Hence this course covers a wider range of subjects, contains a larger amount of information, but no less of that which is precise, accurate, and disciplinary, than if it were intended exclusively for the smaller class of students who are in preparation for college.

To Professor E. W. Wetmore, of the New York State Normal College, who has read the entire work in proof sheets, and has enriched it in many places, I desire to express my gratitude. To Mr. James F. McElroy, Albany, N. Y., I am indebted for the cuts illustrating his explanation of the production of motion in the electric motor. My thanks are due also to Mr. George C. Gow, professor of music in Vassar College, who has read the chapter on Sound, and to my daughter, Mabel Lillias Cooley, who made nearly all the drawings for the illustrations in the book.

L. C. C.

MAY, 1897.

LABORATORY WORK.

THE educational value of laboratory work depends entirely on the way in which it is done. It rewards the student just in proportion to the care he bestows on it, and the effort which he makes to secure accurate results.

The purpose of all the experimental work described in this book is threefold: To illustrate the general principles of the science, and thus to impress them more deeply on the mind; to acquaint the student with experimental methods of reaching and verifying truth; to cultivate the habit of thoughtful observation, and the power to reason logically and to express thought correctly. With these objects in view the following suggestions are made:

No experiment should be undertaken without adequate preparation. Only when a student has studied the general principle involved, knows the specific object to be accomplished, and something about the instruments to be used, is he ready to begin. Therefore he should study the text, and read carefully through the directions for making an experiment before entering the laboratory.

Next in importance to the ability to reach truth by experimental means, is the power to express it with clearness and accuracy. Hence a methodical record of all laboratory work should be made. A notebook should be devoted exclusively to this purpose. Let it be an ordinary blank-book, about ten inches long by eight inches wide, with stiff covers, made of ruled paper with numbered pages and a marginal line. A

chronological history of the work in each experiment should be briefly noted on the left-hand page, while the right-hand page should be reserved for sketches of apparatus, the record of incidental observations and arithmetical computations. The following order is recommended:

Date —— ——. Experiment No. ——. (To be recorded at the top of the left-hand page of the open notebook.)

Object ——. (To be copied from the text-book.)

Apparatus. — Collect the necessary pieces of apparatus, arrange them ready for use, and then record their names, and designate each by the number, or other label, which it bears.

Observations. — Proceed to use the apparatus just as directed in the instructions given. Note briefly but clearly each step in the work and inferences or data obtained from it. For example, suppose the experiment has for its *Object:* To measure the volume of a small piece of marble to the nearest .1 cc. by displacement of water. Step by step the work should go on, each step being immediately described somewhat as follows:

I read the volume of water in the cylinder — found, 20.5 cc.

Suspended the marble by a fine silk thread.

Immersed it in the water, noticed air bubbles clinging to it. Rinsed them off by lifting and lowering the marble.

Read the volume of both water and marble — found, 23.8 cc.

Watch for everything which occurs; *let nothing escape attention.* Incidental observations may be recorded on the right-hand page. Do not stop to make any computations while the experiment is in progress, unless a result is needed for use in the work..

Computations. — After the experimental work is finished, proceed as follows to make the computations: On the left-hand page indicate the operations in equational form only. Then let the arithmetical work be done, neatly and compactly,

on the right-hand page opposite, and the result be transferred to its place on the left. Much time and labor will be saved if the details of the computations are preserved in this way so that they may be reviewed quickly in search for errors. Let none be made on loose scraps of paper. Whenever possible, collect the observed and computed values in a tabular form. In many cases such tabular forms are given in the book.

Conclusion.—Write a brief summary of results. This should be so stated as to show that the *Object* of the experiment is accomplished.

No copying from the text-book should be permitted beyond the statement of the object, a working formula, or numerical data. No erasures should be permitted. A new result may be written above the old one and the reason why it is preferred on the opposite page, but the old one should stand distinct; it is sometimes the true one after all.

The records should be criticised by the instructor, the corrections should be made by the student, and, finally, they should be included among the subjects discussed in the class room.

CONTENTS.

I. MATTER AND FORCE.

MATTER.

1. **Matter.**—*a.* Wood, iron, water, and air are different *kinds* of matter. Books, vases, blocks of wood, and iron balls are separate *portions* of matter. Each different kind of matter is called a *substance,* while each limited portion of matter is called a *body.*

b. Each substance differs in some way from every other. One is hard, another soft; one is flexible, another brittle; and many other differences are noticed when we examine and compare different substances. Hardness, flexibility, brittleness, elasticity, and all other qualities are called *properties of matter.*

A substance may have some properties which it cannot show without changing into other kinds of matter. For example: Combustibility is a property of wood, but you cannot detect that property without actually burning the wood, and when the wood burns it is no longer wood; it is reduced to ashes and vapors. But other properties, such as hardness and color, can be detected without producing any change in the substance. So we see that there are two classes of properties. Those which a substance may show without changing into other kinds of matter are called *physical properties.* Those which a substance can not show without changing into other kinds of matter are called *chemical properties.*

Our study of Physics is chiefly devoted to physical properties, and those which we should first consider are *extension, mass,* and *density.*

2. **Extension.** — *a.* Extension is that property of matter in virtue of which a body occupies space. The extension of a body is in all possible directions, but all directions are included in the three dimensions known as length, breadth, and thickness.

> Length is extension in one dimension only.
> Area has extension in two dimensions.
> Volume has extension in three dimensions.

It is quite clear that length is the fundamental quantity; for if we can measure length, we can find area, which is the product of two lengths (one of which is called breadth), and also volume, which is the product of three lengths (one of which is breadth and another is thickness).

b. In order to measure length, two things are necessary: There must be a *unit* and also a *standard.* A unit of length is a certain distance which has been chosen, with which to compare all other distances, and a standard of length is a bar on which that distance is marked with precision and by authority, in order to insure uniformity and accuracy in its use.

Two units have been chosen. One was fixed by the English government and adopted by the United States; it is called the *yard.* The other was fixed by the French government, and has been legalized by the United States; it is called the *meter.* The two standards on which these units are marked are certain bars kept in the custody of officials of these nations.

c. In the office of the standards in London is a bronze bar, near each end of which is a gold plug. Across the head of each gold plug a fine line is engraved perpendicular to the length of the bar. The distance between the centers of these two lines, when the temperature of the bar is 62° F., is the English unit of length, or yard. An act of Parliament made it the unit, and at the same time declared this bar to be the standard.

d. In the French Archives there is a rod of platinum. The distance between the ends of this rod, when the temperature of the rod is 0° C., is the French unit of length, or meter. An act of the French government made it the unit, and at the same time declared this bar to be the standard.

e. Smaller units than the yard or the meter are more convenient when short lengths are to be measured, and hence the yard and the meter are subdivided. The yard is divided into 36 equal parts, each called an *inch*, and a *foot* is fixed as 12 inches. The meter is divided into 10 parts called *decimeters*, each of these again into 10 parts called *centimeters*, and each of these into 10 parts called *millimeters*.

Larger units, more convenient for measuring long distances, are obtained by taking multiples of the smaller units. Thus the English *mile* is 5280 feet, and the French *kilometer* is 1000 meters.

The inch is the English unit most used in the laboratory, and the centimeter is the most convenient French or metric unit, because the distances to be measured are generally small in laboratory experiments.

f. Throughout this book the centimeter will be the metric unit of length in laboratory work, and millimeters will be written as tenths of a centimeter. Thus twenty-five centimeters and six millimeters will be written 25.6 cm., instead of 25 cm. 6 mm.

3. **Operations for measuring Extension.** — A. *Lengths.* *a.* A *meter bar* is a bar of wood or metal with an accurate copy of the scale of the standard meter (§ 2, *d*) engraved upon it. Its *least count*, that is, the smallest length marked upon it, is one millimeter (.1 cm.). Fig. 1 shows a part of a meter bar placed as it should be to measure a length, — say the length of the upper front edge of a block. Notice that the measure is placed *on its edge*, thus bringing its scale lines into contact with the line to be measured. Notice also that *the end of the bar is not used;*

some other division is placed at the end of the line which is to be measured. This is so because the end divisions are not always true. The end may not be cut perfectly square or it may be worn. The length is found by reading the scale at

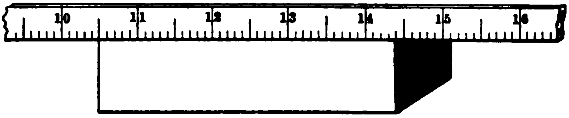

Fig. 1.

each end of the line and taking the difference between the two readings. Thus, according to the figure, the two readings are 14.4 cm. and 10.5 cm. So the length of the line must be 14.4 – 10.5, or 3.9 cm.

b. But the length of a *body* is not likely to be the same at all points, even when its ends are supposed to be cut squarely. By the "length of a body" we mean its *average* length. To find the average length of the block, Fig. 1, for example, we measure it along all four of its edges, and perhaps at other places, then add all these lengths, and divide the sum by their number.

c. It is practically impossible to measure anything with absolute exactness. There are distances too small for the eye to see, and human skill fails to handle instruments with absolute precision. Besides this, there is the fact that the scale divisions of a measuring instrument are not absolutely correct. But it is possible to measure lengths with very little error, and a certain degree of exactness is required in every case.

The accuracy required is not the same in all cases. An inch is a large error in the length of a table; it would be a very small one in the distance between two cities. The tenth of a centimeter is a large error in some measurements which the student is called on to make, and the thousandth

of a centimeter is too large for certain purposes in science. *The student should spare no effort needed to reach the desired degree of accuracy in every case.* And then he should remember that the time spent in reaching a still higher degree is wasted.

Experiment 1. — *Object.* To measure the outside dimensions of a rectangular block to the nearest millimeter; that is, to within .1 cm.

Use a meter bar as directed in *a*. Find the average value of the length, reading the scale with great care. To read a scale correctly, always put the eye directly in front of the division line to be read. Record the results of the work, *each as soon as obtained*, in the notebook, using the centimeter as the unit. Thus 4 cm. and 3 mm. should be written 4.3 cm. The record may be in the following form:

A. *Measurement of the Length.*

Upper front edge	15.7 cm.
Lower front edge	15.9 "
Upper rear edge	16.0 "
Lower rear edge	16.1 "
Average	$63.7 \div 4 = 15.9\cancel{25}$ cm.

Notice that while the computation gives 15.925 cm. we reject the .025. We do so because the *actual measurements* were made only to tenths. The .025 is useful simply to show that the result is *nearer* 15.9 than 16.0 cm.; hence we conclude that the true length is 15.9 cm. *to within* .1 cm. Always remember to use this method when you compute results from experimental data.

In the same way find the average width, *B*, and the average height, *C*, of the block.

Follow the directions given for making an experiment carefully, but not thoughtlessly. Try to know *why* the work should be done in just that way. Test the need of it by trying to do the work some other way. Thus: Place the meter bar *on its side* along the line to be measured, and *see* why it should be placed on its edge. Try to read the scale by placing the eye not directly in front of the division mark to be read.

Experiment 2. — *Object.* To measure the diameter of a ball to within a millimeter (.1 cm.).

Place the ball between two square-cut blocks, *a* and *b* (Fig. 2), whose faces are pressed against a third block, *c*. Measure the distance across from *a* to *b* with a meter bar pressed against the faces of *a* and *b*. Measure the diameter of the ball in several directions. Record each observa-

tion as in Experiment 1, and compute the average. To obtain a correct result, the faces of the blocks must be cut truly "square," and the thickness of *a* and *b* must exceed the half diameter of the ball. Study the operation until you can give reasons for these precautions.

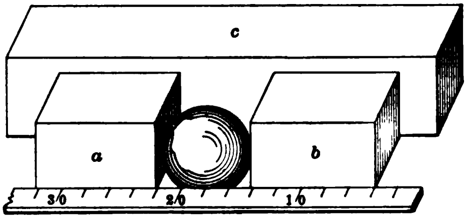

Fig. 2.

Experiment 3. — *Object.* To measure the diameter of a small wire to within .01 cm.

Since the "least count" (§ 3, *a*) of the meter bar is .1 cm., we cannot read to the .01 cm. directly, and hence we must resort to some indirect way to measure to this higher degree of accuracy. Wind the wire around a rod, perhaps a lead pencil, *making every turn lie closely against the one before it*, until two or three centimeters of the rod are covered (Fig. 3). There must be *at least* ten turns. Open a pair of dividers (Fig. 4), or calipers, until they will just embrace the length of the coil *ab*. Set the points on a meter bar, and read the length of the coil on the scale. Count the number of turns of wire in the coil. Divide the length of the coil by the number of turns. The quotient carried to hundredths' place will be the diameter of the wire to within .01 cm., for the length *ab* can be read directly to the nearest .1 cm. The error cannot be *more* than this, and with care you can be confident that it is less than the half of it. But suppose the error to be the whole of .1 cm.; since it is the error on *ten* diameters of the wire, the error on one diameter is only .01 cm. If the number of turns is more than ten, the *total* error will be no greater, and the measurement of the one diameter will be still more exact. How would you get the diameter of a wire to within .001 cm.?

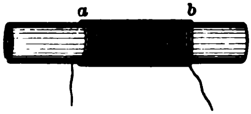

Fig. 3.

Fig. 4.

Experiment 4. — *Object.* To compare the English and the metric units of length.

Apparatus. A yardstick. A meter bar. Dividers or calipers.

After reading the following directions, and before beginning the operations, construct the tabular form as shown below, in which to record the observed numbers.

Operations. Place one point of the dividers on one of the inch marks of the yardstick, and open the dividers until the other point stands

on another inch mark several inches away. Read the scale at each point and note the two readings in the table. Without opening or closing the dividers, transfer them to the metric scale, placing one point on one of the centimeter marks. Read the scale at each point, and note the two readings in the table. *Repeat* these operations three or four times, taking a different distance between the points of the dividers, and using different parts of the yardstick and the meter bar, for each trial.

No. of Trials.	Scale readings.		Scale readings.		Distance *ab*.	Cent's = 1 inch.
	a.	*b.*	*a.*	*b.*		
1	—— in.	—— in.	—— cm.	—— cm.	—— in. = —— cm.	——
2	—— "	—— "	—— "	—— "	—— " = —— "	——
3	—— "	—— "	—— "	—— "	—— " = —— "	——

Computations. Find the distance between the points of the dividers, first in inches, then in centimeters; it is the difference between the scale readings on the yardstick and meter bar respectively, in each trial. Enter these in the table.

Find the *number of centimeters equal to one inch* in each trial. Enter these in the table. The results of several trials are expected to differ (§ 3, *c*); but if the experiments have been well made, the difference will be small. No single result is likely to be accurate; one may be too large, another too small. Each is just as likely to be too small as too large. In every such case the *average* is nearer the truth than any one of the separate values. Hence, find the average (§ 3, *b*) of all the values obtained, and report your conclusion; thus:

1 inch = —— cm. to within —— cm., an average of —— trials.

Compare your observed value with the value to be found in the books.

Knowing this equivalent value of the inch and the centimeter, the equivalent values of other units may be found.

Compute the number of centimeters in one foot; in one yard. How many inches in one meter? (Appendix I., *d.*)

B. *Volumes.* *a.* The laboratory unit of volume is the cubic centimeter (cc.). The volume of a rectangular solid may be computed if the average length, breadth, and thickness have been measured (§ 3, A, *a*). Thus compute the volume of the block whose dimensions have been measured in Experiment 1.

But this method cannot be used to measure the volumes of liquids, nor of irregular solids.

b. For measuring the volumes of liquids, *graduated vessels* are employed. These are usually cylindrical glass vessels with scales etched upon them. Their sizes and shapes are various. Two are shown in Fig. 5. *A* is a "graduated cylinder," and *B* is a "conical graduate." To measure the volume of a liquid, we put it into the measuring glass, and read the scale division at its surface. But the surface of a liquid, especially in a narrow vessel, is not quite flat; wherever it touches the walls it is curved. In the case of water and other liquids which we are liable to meet with, except mercury, the surface is lifted, as shown in Fig. 6. *The scale mark on which the lowest point of the curved surface rests,* is the one to be read; and in order to read it correctly, *always place the eye on a level with the mark.* Why? The vessel *must be vertical.* Why?

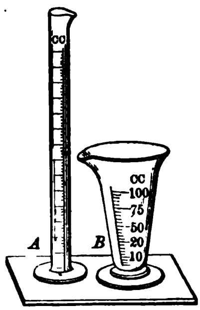

Fig. 5.

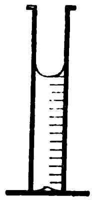
Fig. 6.

c. The volume of an irregular solid may be readily measured by immersing it in water in a graduated cylinder. For a solid, which does not dissolve, must displace just its own volume of water when it is wholly immersed, and the volume of water displaced is shown by the scale on the cylinder.

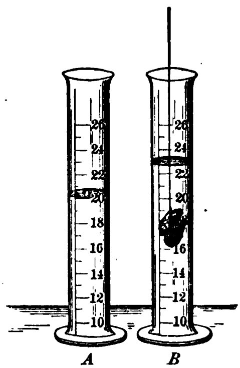

Fig. 7.

Experiment 5. — *Object.* To find the volume, in cubic centimeters, of a fragment of stone or some other insoluble substance.

Fill a graduated cylinder (*A*, Fig. 7), exactly to a certain mark with water. In doing this bear in mind the three precautions emphasized in *b*. Note the number of cubic centimeters, reading to the least

count of the scale. The stone may then be dropped with care into the water, or suspended by a *fine* thread (*B*, Fig. 7). Any clinging air bubbles must be shaken off. The scale reading now shows the volume of the water and stone together, and the difference between the two readings is the volume of the stone. The record in the notebook may take this form:

Volume of the water alone	25.5 cc.
Volume of the water and stone	30.8 cc.
∴ The volume of the stone is	5.3 cc.

d. The volume of a solid body is not always the volume of the substance in it. If we take 25 cc. of small shot in a measuring glass, we do not get 25 cc. of lead. No porous or granulated substance fills all the space it appears to occupy. Why?

Experiment 6. — *Object.* To find the volume of sand in 25 cc. of dry, coarse sand, by displacement of water.

Fill a graduated cylinder to the 25 cc. mark with the sand, taking care to make its surface flat. Put more than 25 cc. of water into another graduated cylinder, and read its volume accurately. Pour the sand into the water, and faithfully remove all the air from the sand. If you use a glass rod to stir it, let the last drop of water fall back into the jar when you take it out. Record your results as in Experiment 5.

4. **Mass.** — *a.* By the *mass* of a body we mean the quantity of matter it contains. The word is also used in another sense; bodies themselves are called *masses.* In what follows, this sense is not intended; mass refers to quantity of matter.

b. We cannot judge of the mass of a body by its size. There is more matter in an iron ball than in a wooden ball of the same size (why?), and the same iron ball is larger when hot than when cold. Mass is not proportional to volume, but to another property called *inertia,* which must now be defined.

c. We know by experience that bodies resist our efforts to move them, or to stop them when in motion. Sir Isaac Newton first pointed out the following law, which is known as Newton's First Law of Motion:

If a body at rest were left entirely to itself, it would rest forever, or if in motion, it would move forever without any change in its direction or its speed.

Now that property of matter by virtue of which a body opposes any change whatever in its existing condition of rest or motion, is called *inertia.*

d. You can detect the existence of inertia in a "nickel" by the following simple experiment:

Experiment 7.—Place a visiting card, with a string attached to the middle of one end, on the top of an upright spool (Fig. 8), and lay the coin on the card as shown in the figure. Pull the string suddenly in a horizontal direction; you should thus twitch the card off the spool but

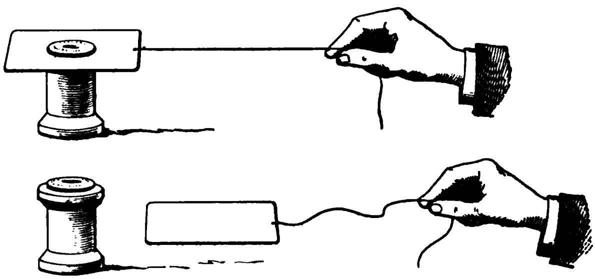

Fig. 8.

leave the coin behind. The nickel resists the force which moves the card, else it would go with it.

Repeat the experiment, but pull the card away gradually; the coin will not be left behind. The inertia is the same as before, and the pull may be no greater, but it lasts longer. Time is required to transmit, from the card to the coin, the energy by which the inertia is overcome.[1]

e. We connect inertia with quantity of matter in this way: *It is a property of matter,* not of any one kind of matter alone, but of all kinds. We may therefore fairly infer that the more matter there is, the more inertia there must be. So a body which requires a stronger pull to put it in motion than another requires under the same conditions, contains a larger quantity of matter.

[1] See Daniell's *Principles of Physics* (1894), p. 147.

f. Practically, we can compare the quantities of matter in two bodies by comparing the earth-pull upon them. We know that the earth does pull every body towards itself. Rain-drops, leaves, — all things when not supported, — are pulled to the ground by the earth. Now the *earth-pull on two bodies may be balanced, one against the other. Then, if neither body moves, the two must contain equal quantities of matter.* Let us have a bar (*AB*, Fig. 9) perfectly uniform in matter and size from end to end. Such a bar, if suspended at its middle point, *C*, will be found to rest in a horizontal position. The earth pulls the two halves, *AC* and *CB;* if either were to go down, the other would go up, and if neither can go down, the two pulls are equal. Hence *AC* and *CB* contain equal quantities of matter. For the same reason, if *two bodies,* m *and* n, *balance each other on the opposite ends of a uniform bar supported at its middle point, they contain equal quantities of matter.*

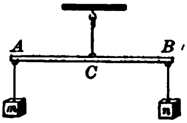

Fig. 9.

g. There are two fundamental units of mass. The English unit is a certain quantity of matter which is called a *pound.* The French unit is another certain quantity of matter which is called a *kilogram.* These units are embodied in standards. The English standard pound is a small block of platinum kept in the office of the standards, London. The French standard kilogram is a block of platinum which is preserved in the French Archives. The quantities of matter contained in these blocks are the units of mass, because they have been declared to be such by the respective governments. A "pound of sugar" is simply a quantity of matter equal to the quantity contained in that "standard pound" in London.

h. Larger and smaller units have been obtained from these fundamental units. A *ton* contains 2000 times as much matter as that in the standard pound, while an *ounce,* avoirdupois, contains $\frac{1}{16}$ as much matter as that in the same platinum block.

The unit of mass in laboratory experiments is the *gram*. The gram is .001 of the kilogram. The subdivisions of the gram are the tenth, or *decigram*, the hundredth, or *centigram*, and the thousandth, or *milligram*. These are usually written and read as decimals of the gram; thus: 8 grams, 5 decigrams, 4 centigrams, and 1 milligram should be written 8.541 g. It should be remembered that a gram is, practically, a quantity of matter equal to that contained in 1 cc. of pure water at 4° C.

5. **Instruments and Operations.** — *a.* The instruments needed to find the masses of bodies are a *balance* and a *box of standard masses*, or, as they are usually but inaccurately called, *weights*. We shall describe two kinds of balance,— the *beam balance* and the *spiral balance*.

b. The beam balance has many forms, but it always involves the same principle,—that which was explained in § 4, *f* and Fig. 9. A common and good form is shown in Fig. 10. Notice the beam supported at its center by a pillar so that its ends may rise and fall with great freedom. Notice the two pans hanging by wire bows from the ends of the beam. Notice the scale at the base of the pillar, and the long pointer which, fastened to the beam, moves along the scale as the beam swings. Notice that all these parts are protected by a glass case. The least count of such a balance is .001 g. (1 mg.). The student rarely needs to reach a higher degree of accuracy than this, and in most experiments .01 g. is sufficiently exact. Balances whose least count is .01 g. are coarser in construction and are considerably less expensive.

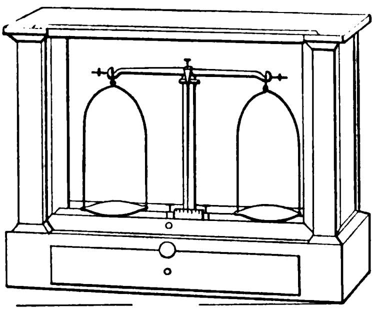

Fig. 10.

c. A set of masses, of known value, are to be used with the beam balance. They are carefully kept in a neat box, as shown in Fig. 11. The smallest of these *box masses,* in the

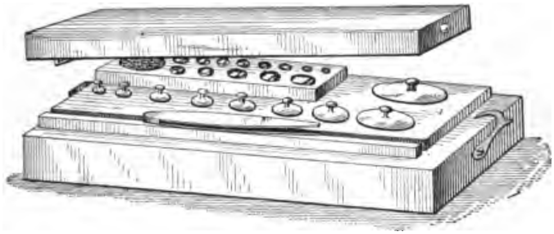

Fig. 11.

front row at the left, is 1 g. Multiples of a gram follow, until we find the largest one at the right, 100 g. The decimals of a gram, arranged each in its own compartment, are shown in the rear; they range from .5 g. down to .001 g.

d. The operation of finding the mass of a body is called *weighing.*[1] It consists in placing the body whose mass is to be found in the left-hand pan of the balance, and then putting box masses into the other pan until the two are balanced (§ 4, *f*). The sum of the box masses used is the mass of the body.

e. But a good beam balance is a very delicate instrument. It must be handled with care, because rough usage will soon and surely render it useless for any accurate work. It should be used by the student under the direction of the instructor, but a few of the main points to be observed are the following:

1. The instrument should be level. Test it with a spirit level, and, if need be, lift the lower corners by putting pieces of paper under them.

2. The pans should be clean. Remove dust by means of a camel's-hair brush.

---

[1] "Weighing" is not the operation of finding the *weight* of a body, but its *mass.* To find weight, something more is necessary, as we shall see (§ 13, *f*). The term has come down from the time when the difference between mass and weight was not clearly seen.

3. The pointer should swing through equal distances on opposite sides of the middle line of the scale. A few grains of sand in one pan will correct any slight deviation, or the instructor may adjust the beam by turning the screws at its ends.

f. By these adjustments the balance is made ready for use. The following directions are to be strictly followed:

1. The beam should *never* be violently jarred or jerked; hence put the masses on the pans gently and remove them carefully.

2. Air currents should not strike the pans; hence the case may be closed, if necessary, after each change of masses on the pan.

3. The moisture of the fingers corrodes the box masses and changes their values; hence handle them with forceps only.

4. Use the box masses in regular order. First find one which is just a little too small. Then add smaller ones, trying them in the order of their places in the box, until the right quantities are obtained. Random choices waste much time.

Experiment 8. — *Object.* To measure the mass of a beaker to the nearest milligram (.001 g.) by means of a beam balance.[1]

Place the beaker, which must of course be clean and dry, on the left-hand pan of the balance, and proceed, under the direction of the teacher, according to the instructions given in *e* and *f*.

Experiment 9. — *Object.* To find the length of a twisted piece or coil of wire, by means of a beam balance and meter bar.

Operations. — 1. Find the mass of the twisted piece or coil as directed in *e*, *f*, and Experiment 8. Denote it by M.

2. Find the mass of a straight piece of wire of the same material and diameter. Denote it by m. Also find the length of this straight piece by the meter bar, and denote it by l. Record the observations thus:

Mass of the straight wire	——g.	m.
Length of the straight wire	——cm.	l.
Mass of the twisted wire	——g.	M.

Computations. Find the average mass of a centimeter of the wire; it

[1] If a coarser balance must be used, find the mass to the least count of the balance.

is $m + l$, or —— $g.$ per cm. Then find the length sought of the twisted wire or coil; it is M ÷ number of grams per centimeter.

g. The action of the *spring balance* depends on the elasticity of a spiral of wire. The principle will be explained in a future paragraph (§ 13), but the use of the balance may be described here, because this instrument is an excellent substitute for the beam balance in much of our laboratory work, and it is less costly than a beam balance of equal accuracy.

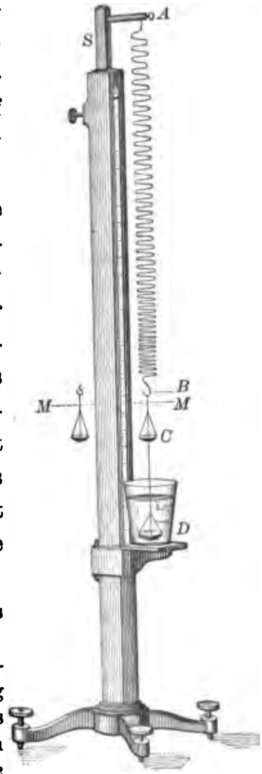

Fig. 12.

Fig. 12 represents the spring balance in its best form, known as Jolly's balance. Notice: A spiral spring, *AB;* scale pans, *C, D;* a scale upon the pillar behind the spiral to measure the elongation produced by a body in *C.* This scale is etched, *in millimeters,* on looking-glass. The index is a white bead just below *B.* The pan *D,* in water, deadens the vibrations, and thus saves time. It is useful also when a body is to be weighed in water.

Experiment 10. — *Object.* To find the mass of a body by means of a Jolly's balance.

Operations.* Put water into *D* until its surface will be above the triangle of supporting wires when the pan swings free from the walls and bottom. Lift *D* until the pan hangs in that position. To read the scale: *Place the eye so that the index is exactly in line with its image in the mirror,* and read the scale division which lies exactly in the line of sight. (It will be half way between the highest and lowest points of small vibrations.) Denote this reading by *m.* This is the starting point, or zero reading, from which all elongations are to be measured. Lower the platform *D;* place the body to be weighed in pan *C;* adjust the height of *D* so that the pan will again be in the center of the water; read the scale again, and denote the reading by *l.

Remove the body from C, and put box masses in its place until the same reading is obtained. The sum of the box masses equals the mass of the body. The record may stand as follows:

Scale reading with empty pan . . . . —— mm. . . *m*.
Scale reading with the —— in the pan —— mm. . . *l*.
Box masses to obtain the same reading, *l*. —— g.
∴ The mass of —— is —— g.

It is desirable to repeat the weighing, and take an *average* as the mass of the body. If possible, adjust the index to a different starting point on the scale by raising the support *S*.

It is not always easy to read the scale, because the lines on the mirror are indistinct. To obviate this difficulty, make a hole about ¼ of an inch in diameter in a small sheet of cardboard. Place the balance *with its back toward a window*. Look through the hole and the scale will appear to be on a dead white surface — the image of the cardboard in the mirror.

6. **Density.** — *a.* A rubber ball is smaller when under pressure than when it is not, but it contains the same quantity of rubber. An iron ball is larger when it is hot than when it is cold, but it contains no more iron. The same mass may have different volumes under different circumstances; so that 1 cc. of it contains different quantities. Think of the volume of cork that would be required to balance a pound of iron; but notwithstanding the great difference in their volumes the masses of the cork and iron would be equal.

The property of matter by virtue of which equal volumes contain different quantities is called *density*.

b. We describe the density of any particular substance by stating the quantity of matter contained in one unit volume.

Thus we have seen that the quantity of matter in 1 cc. of pure water at 4° C. is 1 g. (§ 4, *h*). The density of pure water at that temperature is therefore said to be "1 g. per cc." So likewise we describe the density of cast iron as 7.2 g. per cc.

c. The relation between volume, mass, and density in all cases is illustrated by the following example:

Suppose that a block of marble is 5 cm. long, 3 cm. wide, and

2 cm. thick, and that its mass, found by the balance, is 81.6 g.; what is its density?

The question amounts to this: How many grams are there in one cubic centimeter of this block? The number of cubic centimeters in the block is $5 \times 3 \times 2$, or 30. Hence one cubic centimeter contains $\frac{81.6}{30}$ or 2.72 g. So the density of marble is found to be 2.72 g. per cc.

In like manner the density of any substance may be computed. We may write the general value of density briefly as follows:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}.$$

Example. — The mass of a piece of iron, found by the balance, is 10.56 pounds. The piece is rectangular and measures 6 inches in length, 4.5 inches in width, and 1.5 inches in thickness; what is the density of the iron? *Ans.* 4.17 ounces per cubic inch.

d. The experimental work to be done in order to find the density of a substance consists in measuring the mass and the volume of some convenient portion of it.

The measuring bar and balance are the instruments employed for solids, except when the specimen to be measured is irregular in form, and then the volume may be found by the method of displacement (§ 3, B, *c*). Of liquids, the volumes may be found by means of accurately graduated measuring tubes, and the masses by the balance. But of gases, neither volumes nor masses can be measured by these instruments alone; more complicated methods, which need not be studied now, must be adopted.

Experiment 11. — *Object.* To find the density of marble.[1]

1. A piece of the stone is trimmed to such size and shape that it will easily enter a graduated cylinder. Measure the mass of the stone by a balance (§ 5, *a*).

[1] Or any other solid which can be wholly immersed in water without dissolving. If it be wood, a slender wire may be used to push it below the surface of the water. The volume found will be a little too large on account of the wire, but you can make the error very small if you try.

2. Measure its volume by displacement of water (§ 3, B, *c*).
3. Compute the density (§ 6, *c*).

e. Density, mass, and volume are so related (§ 6, *c*) that any one of the three values can be computed if the other two are known.

$$\text{Density} = \frac{\text{mass}}{\text{volume}}.$$

$$\text{Mass} = \text{density} \times \text{volume}.$$

$$\text{Volume} = \text{mass} \div \text{density}.$$

Examples. — 1. How many grams in a block of cast iron which at a temperature of 4° C. is found to be 15 cm. long, 3.6 cm. wide, and 2.4 cm. thick, if the density of iron at that temperature is 7.2 g. per cc.?

Ans. Mass = density × volume = 7.2 × 129.6 = 933.12 g.

2. How many cubic centimeters in a block of pine wood whose density is .66 g. per cc., its mass, found by the balance, being 75.4 g.?

Ans. Volume = mass ÷ density = 75.4 ÷ .66 = 114.24 cc.

3. Compute the mass of a square-cut granite building stone whose length, breadth, and thickness are respectively 4 feet, 2 feet, 1.6 feet, if the density of granite is 1.5 ounces per cubic inch.

f. If we compare the densities of different substances with that of some one particular substance, the numerical ratios are called *relative densities.* For example: If the density of water is .578 ounces per cubic inch, and the density of cast iron is 4.17 ounces per cubic inch, then the ratio of the density of cast iron to that of water is 4.17 ÷ .578, or 7.2. That is to say, the density of cast iron is 7.2 times the density of water.

The relative density of any substance is the ratio of its mass to that of an equal volume of a standard substance. Unlike density, it is not a concrete, but a numerical, value. (Appendix III., 2.)

7. **The Conservation of Matter.** — *a.* In all the changes which occur in bodies there is neither loss nor gain in the quantity of matter which exists.

This statement seems to contradict some of the most familiar observations. What, for instance, becomes of a candle when it burns away? What becomes of water when it evaporates?

Experiments show that in all such cases the substances

change into other kinds or forms which are invisible, while the quantity remains unchanged. In the case of the boiling water we may catch the vapor in a cold vessel, which will change it back to water, and, by the balance, we can find the same quantity as before the apparent loss occurred.

In any case, by preventing the escape and loss of any portions, we can find by the balance that the quantity of matter after the change is the same as before it occurred.

8. **Studies.** — 1. If one of the small cubes used in playing backgammon, or dice, is just 1 cm. on each side, and it be dropped into pure water at a temperature of 4° C., what mass of water will it displace?

2. If we should find by the balance that the mass of the cube is 1.92 g., what is the density of the substance of which the cube is made?

3. A certain napkin ring was for sale as "solid silver." Now the density of standard silver for such articles, which always contains some copper, is about 10.3 g. per cc. The mass of the ring was found to be 103.2 g. Its volume, found by displacement of ice-cold water, was about 12 cc. Compute the density of the substance in the ring. Then decide whether the ring was good silver, as was claimed by the dealer.

4. If the density of ice is .93 g. per cc., what is the volume of 1000 g. of ice? What is the volume of the same mass of ice-cold water?

5. What is the size, or volume, of the piece of ice which the ice-man should leave daily, who agrees to deliver 175 pounds a week?

THE MUTUAL ACTION OF BODIES.

Introduction. — We have seen (§ 4, *c*) that inertia is a property of matter which causes every body to stay persistently in whatever condition of rest or motion it may be at any time. It cannot change its own condition, and, more than this, every body actually resists every effort from other sources. How, then, can the changes which are constantly going on everywhere be explained? We are now to study this question.

9. **The Mutual Action of Bodies.** — *a.* Whenever any change in the condition of matter occurs, it will be found that at least two bodies are concerned in producing it.

For example: In baseball the motion of the ball is stopped and reversed by the bat. But the ball and the bat are equal partners in these changes. The ball strikes the bat as really as the bat strikes the ball. And in every case *it is the mutual action of different portions of matter that causes whatever change occurs.*

b. This mutual action must overcome every hindrance before any change can take place. Inertia (§ 4, *c*) is always one hindrance; others exist also. For example: It would require an effort to start a carriage, because of its inertia, even if the road were polished glass, or better still, absolutely smooth. When the carriage is on a common road there is the same inertia, and, in addition, there is the resistance due to the roughness of the road. Both of these must be overcome by the mutual action of horse and carriage, in order to start the carriage or to produce any change in its speed after it has been started.

c. All bodies are acting upon one another all the time. If in any case their action is strong enough to overcome every hindrance, *motion* is produced; as when the mutual pull of the earth and an apple causes the fruit to break away from the bough and fall to the ground. If the mutual action of bodies is not strong enough to overcome the resistances, it produces sometimes *pressure* and sometimes *tension.* For example: There is *pressure* of a pile of books upon a table, because the mutual pull of the earth and books is not so strong as the resistance of the table. And when a mass of iron is suspended by a cord from a firm support, there is *tension* in the cord, because the mutual pull of the earth and iron is resisted by the cord.

d. Newton was the first to point out the fact that the action between two bodies is mutual. His Third Law of Motion states that *with every action there is always an equal reaction in the opposite direction.* Action and reaction are the two phases

of the one mutual action, each due to one of the two bodies between which the action occurs.

e. Take the case of two persons (A and B, Fig. 13) pulling against each other by a rope, neither being able to overcome

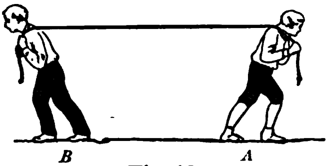

Fig. 13.

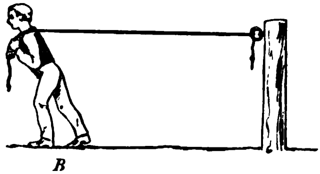

Fig. 14.

the other. Their mutual action consists of two parts: A's pull on B towards the right, and B's pull on A towards the left. These two parts are equally strong and in opposite directions. If B pulls with the same strength against a fixed hook (Fig. 14), the action is the same. It will consist of B's pull to the left and the hook's pull to the right, these two parts being equal in strength and opposite in direction.

f. The same thing is true if the action is a push instead of a pull. Take the case of a boy pushing a loaded car

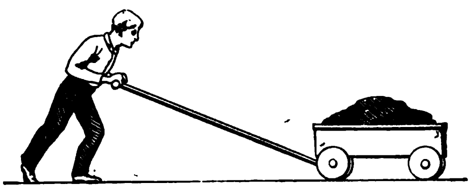

Fig. 15.

(Fig. 15). He pushes against the car, but the car pushes back against him. There is but one action, but it is with equal strength both ways at once.

g. In every case we are likely to ascribe the *action* to the body which we regard as the more important one of the two between which the mutual action occurs, and the *reaction* to the other. Thus when a pile of books rests upon a table

(Fig. 16), we would say that the books *act* upon the table and that the table *reacts* upon the books. But it would be just as correct to say that the table acts upon the books and the books react upon the table. We usually say that the earth acts upon a falling body, and then we should say that the falling body reacts upon the earth. But it would be just as correct to say that the falling body acts, and that the earth reacts.

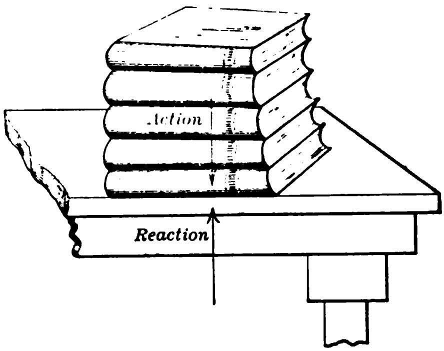

Fig. 16.

h. The mutual action of two portions of matter is generally called *force.* But when using this single word, we should always remember that the action it describes is twofold, consisting of an action and a reaction, and can take place only when at least two portions of matter are concerned.

10. **Motion.** — *a.* Motion may be defined as a continuous passage from one place to another. Now it is evident that two places must be separated by a *distance,* and also that the passage of a body from one place to another must take some *time.* Hence any body in motion must have a *time rate of displacement.* The full meaning of this statement should be understood.

b. Displacement means any change in the place of a body with respect to a given point. A body may be going in a straight line away from a given point; in this case its displacement consists in a change in its *distance* only. But it may be going in the circumference of a circle with the given point as the center; in this case its displacement

consists in a change in its *direction* only. It is easy to see that in other cases displacement may consist in change in both distance and direction.

Time rate means a certain quantity of anything per second or per hour. If a man receive three dollars for ten hours' work, the time rate of his wages is thirty cents per hour. So a *time rate of displacement* means a certain amount of change in distance or direction per unit of time.

c. The time rate of displacement of a moving body is also called its *velocity*. Velocity is often said to be "the distance which a moving body traverses in a unit of time," but this definition is at fault because it does not clearly involve the idea of change in direction. The time rate of a moving body without regard to the direction of displacement, is now called *speed*. The *velocity* of a ball thrown from the hand includes the rate at which it moves away, and at the same time the rate at which its direction changes. Its *speed* is the rate at which its *distance* changes. Thus we speak of the speed of a bullet as, say, 500 feet per second.

d. But it is well known that the velocity or speed of a body does not usually remain the same for any great length of time; it may not remain constant even for a second. It must be understood that we mean the *average* velocity or speed, whenever we assign a value. If we say that the speed of a bullet is 500 feet per second, we should mean that if its time rate did not change, its displacement would be 500 feet per second. But perhaps it starts with a rate which, *if kept up*, would carry it 550 feet a second, and at the end of the second has a rate of only 450 feet per second. The distance it goes in the second is ($550 + 450 \div 2$) 500 feet — *the same as if it had started with a rate of 500 feet per second and kept it to the end.* This 500 feet per second is the average velocity of that bullet. A motion in which the average velocity is the same in successive seconds is called *uniform motion.*

e. The numerical value of a velocity or speed in a uniform motion is found by dividing the whole distance which a body goes in a given time by that time. For example: If a ball rolls, on smooth ice, a distance of 100 feet in 5 seconds, its average speed is 100 ÷ 5, or 20, feet per second.

$$\text{Velocity} = \text{distance} \div \text{time}.$$

In any motion, however varied, the whole distance passed over, divided by the time it took, will give the *average* velocity.

11. **Motion as a Measurable Quantity.** — *a*. Newton pointed out three "Laws of Motion." We have stated the first and the third already. The Second Law of Motion states that *any* CHANGE *of motion is proportional to the force which produces it, and takes place in the direction of the straight line in which that force acts.*

b. Suppose a mass of 10 g. and a mass of 1 g. are to be put in motion with equal velocities, with no hindrances except inertia. The mass of 10 g. will take ten times as much force as the mass of 1 g., because its inertia is tenfold greater (§ 4, *e*). But Newton's Law says that the motion produced is proportional to the force which produces it. Hence there is ten times as much motion in the 10 g. as in the 1 g. And in general: *The quantities of motion in bodies, when their velocities are equal, are proportional to their masses.*

c. But it takes ten times as much force to impart ten times the velocity to the same mass, because, again, there is ten times as much inertia to overcome. And, according to the law, there is ten times as much motion produced. In general: *The quantities of motion in bodies, when their masses are equal, are proportional to their velocities.*

d. We may briefly write the two facts just stated as follows:

Quantity of motion *varies* as mass × velocity.

And when the numerical values of the three quantities are found, we have:

$$\text{Quantity of motion} = \text{mass} \times \text{velocity}.$$

Thus if 50 g. is moving at the rate of 25 cm. per second, the numerical value of its motion is 50×25, or 1250. This product — mass $\times$ velocity — is, in physics, called *momentum.*

$$\text{Mass} \times \text{velocity} = \text{momentum}.$$

Example. — A building stone whose mass was 150 pounds, fell from the wall. Its speed, of course, increased as it went down, but it was 64 feet per second when the stone struck the ground. What was its momentum when it struck? *Ans.* 9600 units of momentum.

A *unit of momentum* is the momentum of a unit mass with unit velocity. No name has been assigned to this unit.

12. **Force as a Measurable Quantity.** — *a.* There is no way to measure the mutual action of two bodies directly, but we can measure its effects. By measuring its effects we indirectly measure force itself. Now the effects of force are *motion, pressure,* and *tension.* We will first explain how a force may be measured by the motion it produces, and afterward explain and describe the method of measuring it by the tension it produces.

b. If we use *momentum* in place of the indefinite term *motion,* Newton's Law declares that *force is proportional to the change of momentum which it produces.* In other words:

Force *varies* as mass $\times$ change in velocity.

The term *acceleration* is useful at this point. It is used instead of the expression *change in velocity. Acceleration* is the velocity which is either added or subtracted per second. Hence we have:

Force *varies* as mass $\times$ acceleration.

If these three quantities are measured in their proper units, and if we use initial letters for words, we have:

$$F = M \times a.$$

For example: If the velocity of 50 g. at the end of the first second has been found by experiment to be 10 cm., and at

the ends of succeeding seconds to be 20, 30, and 40 cm. per second, its acceleration is 10 cm. per second, and the force which produces the motion is

$$F = 50 \times 10, \text{ or } 500, \text{ units.}$$

c. There are two units of force, which are known as the *poundal* and the *dyne.* A poundal is the force required to increase or diminish the velocity of 1 pound by 1 foot per second. A dyne is the force required to increase or diminish the velocity of 1 g. by 1 cm. per second.

Examples. — 1. If a stone whose mass is 75 pounds is rolling down hill, and its speed *increases* at the rate of 20 feet per second, what is the strength of the earth-pull which causes the motion?

Ans. 75 × 20, or 1500 poundals.

2. If the mass of the rolling stone is 35 kilograms, and its speed increases at the rate of 8 meters per second, what is the strength of the earth-pull which causes the motion? *Ans.* 35,000 × 800, or 28,000,000, dynes.

13. **Force measured by Tension.** — *a.* The measurement of forces by the tension they produce is carried out by means of an elastic spiral of wire. *The elongation of a perfectly elastic body is proportional to the force which stretches it.* Thus: If a spiral of spring-brass wire (*ap*, Fig. 17) is fixed at one end, *a*, it will be stretched by any pull downward on the other end. For example: A ball may stretch it until its length becomes *ap'*. If the spiral were perfectly elastic, the pull of two such balls would elongate it just twice as much, three times the pull three times as much, and so on. But if the strain has not been too great, the spiral will afterward return to its original length. Hence, we may take the elongation of the spiral, *bc*, *bd*, and so on, which we can

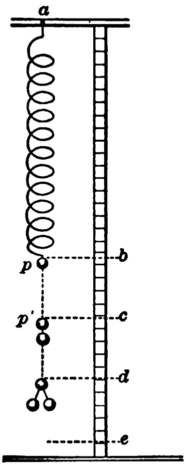

Fig. 17.

measure by a linear scale, as the measure of the force, which we cannot measure directly.

b. The *spring balance* (Fig. 18) is an instrument for measuring forces by the elongation of a spiral spring. The spiral is inclosed in a metallic case with a ring at one end. It is fixed at that end and carries an index, *i*, at the other. To the index end a rod and hook are attached. Each scale division shows the elongation of the spring by any pull equal to that of the earth on a unit mass, — as a gram, or an ounce.

Fig. 18.

Jolly's balance (Fig. 12) is a spring balance of finer construction for laboratory uses. It is more accurate because its spiral is more nearly perfectly elastic.

c. The *units* of force, for commercial uses, are, first, the *earth-pull* on a pound or an ounce, and second, the *earth-pull* on a kilogram or a gram. These are called the *gravitational units of force.*

But these gravitational units do not have the same value the world over, because the earth's attraction on the same mass is stronger at some places than at others. They are *variable units.* For scientific purposes *absolute units,* — that is, units whose values are the same the world over, — are used. These are the *poundal* and the *dyne* (§ 12, *c*). They are invariable because they are the forces which overcome the inertia of certain definite masses, and the mass of a body is the same the world over.

d. Now it has been found by experiment that, in the latitude of New York, the earth-pull will add a velocity of 32.16 feet per second every second to a pound which is falling freely. Hence the earth-pull on a pound at places in that latitude is 1×32.16, or 32.16, poundals. Likewise the earth-pull on a gram has been found to add a velocity of 980 cm.,

and hence its value is 980 dynes. So a pound stands for 32.16 poundals, and a gram for 980 dynes, *at all places in the latitude of New York.* In different latitudes their values in poundals and dynes are different.

e. All this being known, it is evident that a force may be measured by causing it to elongate the spiral of a spring balance; then finding the box masses which will produce the same elongation; and then multiplying the pounds by 32.16, or the grams by 980, as the units used are English or French.

Experiment 12. — *Object.* To measure the earth-pull on any convenient body by a spring balance.

1. Suppose we have a well-made spring balance graduated to pounds or grams, — that is to say, the division marks showing the elongations of the spring by the earth-pull on pounds or on grams. Place the body upon the hook or in the pan; hold the balance *vertically;* read the index carefully by putting the eye on a level with it, and if the index has width, be sure to read the edge to which the graduation has been adjusted. Then multiply the reading obtained in pounds by 32.16 for the force in *poundals*, or, if in grams, by 980 for the force in *dynes.* Such balances are not expected to give the most accurate results, but with care they may be trusted for accuracy to the least count of their scale. They must be so placed that there will be the least possible friction in the motion of the spring.

2. Suppose we have a Jolly's balance. Proceed, as directed in Experiment 10, to find the mass of the body. Then find the force by multiplying by the appropriate factor, 32.16 or 980. Read the scale with great care, and if the spring is sufficiently fine to warrant the correction of slight errors, consult a larger work on physics for the correct factor for the latitude nearest to that of the place where your experiment is made.

f. The *weight* of a body is the measure of its earth-pull. Weight is not matter at all; it is force, and is measured in poundals or in dynes. The weight of a pound is 32.16 poundals, because the earth-pull will increase the speed of a pound at the rate of 32.16 feet per second. The weight of a gram is 980 dynes, for a similar reason. To find the *weight of a body* by a Jolly's balance, first find its mass and then multiply by the proper factor (*e*).

II. WORK AND ENERGY.

DEFINITIONS AND MEASUREMENTS.

14. **Work.** — *a.* What is called *work* in science consists in putting matter in motion or changing its speed or its direction. To illustrate: Work is done upon a baseball by the hand which pitches it. And again, work is done upon the ball by a bat which sends it away in another direction. Work is done by the arm which swings the bat, and by the hands which, by catching the ball, stop its motion.

In every case some *resistance*, or opposing force, must be overcome in order to put a body in motion or in any way to change the motion after it is produced. There is inertia always, and there are friction, back pressure of air, gravity, — as the earth-pull is called, — and other opposing forces. To do work is to overcome such forces, and actually to produce motion, or some change in a motion already taking place.

b. The work to be done in any case varies as the resistance to be overcome and also as the distance through which the motion is to occur. For example: The resistance when a body is lifted is the earth-pull, or gravity. We must do 10 times as much work to lift 10 pounds as to lift 1 pound, because the earth-pull against us is proportional to the mass, and we do twice as much work to lift 10 pounds 2 feet high, as to lift it 1 foot, because the resistance is repeated. In every case we may write briefly,

Work *varies* as resistance × distance.

And if we can get numerical values for work and resistance as well as for distance, then

$$\text{Work} = \text{resistance} \times \text{distance}.$$

This is the general equation, true in all cases.

c. Let us see that resistance and work have numerical values when a body is lifted vertically. Place a pound of iron or other substance on a table at the foot of a yardstick held vertically (Fig. 19). Lift the pound until its base is just even with the 1-foot mark. This requires a definite amount of work, which is called a *foot-pound.* Next lift the pound to the height of 2 feet from the table. In this case you do 2 *foot-pounds* of work, and if you lift the pound to a height of 3 feet, you do 3 *foot-pounds* of work. Lift another mass of 5 pounds to the same height, and you do 5 × 3, or 15, *foot-pounds* of work. In doing work against gravity, the resistance is always proportional to the mass, and hence mass, which is easily measured, is taken to represent its value. The general equation becomes:

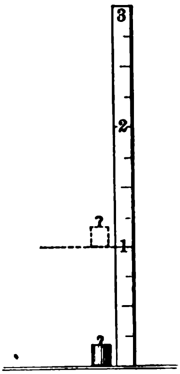

Fig. 19.

$$\text{Work} = \text{mass} \times \text{distance}.$$

Example. — A man carries a hod of bricks whose mass is 50 pounds up to the top of a wall whose vertical height is 60 feet. How much work does he do?

Ans. Work = mass × distance = 50 × 60 = 3000 foot-pounds.

Thus work done against gravity is measured in terms of the *foot-pound,* which is the English *gravitational unit of work.*

d. The metric gravitational unit of work is called the *kilogrammeter.* It is the work done whenever a kilogram of anything is lifted to a vertical height of one meter. For example: If the mass of a person is 75 kg., and he climb a ladder to a vertical height of 15 m., the work which he does

in lifting himself amounts to 1125 kilogrammeters. Work = mass × distance.

A smaller metric unit of work is called a *gram-centimeter.* It is an amount of work equal to that which is done when 1 g. is lifted to the height of 1 cm.

e. Since work depends on resistance and distance only, it is evident that if these two are known, we can find the work done in any other direction as easily as in a vertical direction. Any kind of resistance is *equivalent* to a resistance due to gravity, and we can therefore find the work done in overcoming it by finding its equivalent work done in lifting a mass. For example: We may find the work done by an archer who bends his bow by pulling the string out 15 inches, or $1\frac{1}{4}$ feet. The stiff bow resists his horizontal pull on the string as much as, say, 12 pounds would resist his pull in a vertical direction. If so, then the equivalent gravity resistance is that of 12 pounds, and for the work done in bending the bow we have:

$$\text{Equivalent mass} \times \text{distance} = 12 \times 1\tfrac{1}{4} = 15, \text{ foot-pounds.}$$

Example. — If a bullet pierces a board to the depth of 3 cm. against an average resistance of 150 kg., how much work does it do?

Ans. $150 \times .03 = 4.5$, kilogrammeters.

f. The foot-pound and kilogrammeter are the practical units of work used by engineers. But they have not the same value the world over, because the earth-pull on a pound or a kilogram is stronger in some localities than in others. Like the pound and the kilogram they are *variable units,* whereas for scientific uses *absolute units* are needed (§ 13, *c*).

15. **Absolute Measure of Work.** — *a.* All resistances are of the nature of force. In fact, every resistance is equivalent to the force which must be applied to produce motion in spite of it. On this ground we may speak of a resistance as so many poundals or so many dynes. A pound of matter takes one poundal of force to change its speed at the rate of 1 foot per

second (§ 12, *c*); so the resistance of one pound against any agent which would change its speed at that rate is 1 poundal. The resistance of 1 g. against any agent that would change its speed at the rate of 1 cm. per second is 1 dyne. Thus, for the work done in any case we may write:

$$\text{Work} = \text{force} \times \text{distance}.$$

b. If we measure the force in poundals, the work will be found in units called *foot-poundals*. *A foot-poundal is the work done by or against a force of one poundal working through a distance of one foot.*

If we measure the force in dynes, the work will be found in units called *ergs*. *An erg is the work done by or against a force of one dyne working through a distance of one centimeter.* The foot-poundal and the erg are the absolute units of work.

Example. — A stone whose mass is 35 kg. rolls down a hill with an acceleration (§ 12, *b*) of 4 meters per second, until, having gone 500 meters, it is stopped by a rock; how much work was done by gravity to produce the motion?

Mass = 35,000 grams.
Force = 35,000 × 400 = 14,000,000, dynes.
Work = 14,000,000 × 50,000 = 700,000,000,000, ergs.

c. We have seen (§ 13, *d*) that the weight of a gram is 980 dynes in the latitude of New York, and that the weight of a pound in that latitude is 32.16 poundals. Hence:

The weight of a kilogram is 980,000 dynes.
One kilogrammeter is equal to 98,000,000 ergs.
The weight of a pound is 32.16 poundals.
One foot-pound is equal to 32.16 foot-poundals.

How many kilogrammeters of work was done on the rolling stone in the example above?

16. **Power.** — *a*. The amount of work done does not depend on the time taken to do it. Nevertheless, when work is to be paid for, as in all industries, the time occupied is important. The value of an agent, whether it be a man, or a horse, or a

steam engine, depends on the rate at which it can do the work assigned it. *The rate of doing work* is called *power.*

b. A *unit of power* is work at the rate of a unit per second. The English unit is one foot-pound per second. The metric unit is one kilogrammeter per second.

For larger powers, such as that of a steam engine, larger units are more convenient. Such is the *horse-power,* which is work at the rate of 550 foot-pounds per second. Thus a 10 H. P. engine is one that can do work at the rate of 550 × 10, or 5500, foot-pounds per second. *Activity* is another name for power

$$\text{Horse-power} = \frac{\text{pounds} \times \text{feet}}{550 \times \text{seconds}}.$$

Example. — The mass of a cubic foot of water is about $62\frac{1}{2}$ pounds. If 100 cubic feet of water per minute must be raised 150 feet to a reservoir, what must be the horse-power of the engine used?

17. **Energy.** — *a.* A body in motion can do work on other bodies. For example: In the game of marbles, when one of the elastic balls strikes another it does work, which consists in driving the other from its place. But after striking the other the ball is soon at rest, and the moment it stops it ceases to do work. Its capacity for work is exhausted. *The capacity to do work* is called *energy.* Thus there was energy in the moving marble, and when that marble struck another, it expended its energy to drive the other away.

Work is always done at the expense of energy. In order to do work of any kind, energy must be spent by the body which does it. This law is even more imperative than that in order to buy anything money or its equivalent must be spent by the purchaser.

b. But no body can expend energy without having first received it from some other body or from some force. Referring to the marbles again: The energy of the first, which it expended in driving the second one away, was received from the

hand of the player; and the hand received it from the food which had been previously assimilated in the body.

In the absence of the marbles themselves, Fig. 20, which shows four steps in the action, will be useful. In the first, energy is going out of the hand into the marble. In the second, that energy is stored in the marble in motion. In the third, the energy is going from the marble into another at rest. And finally in the fourth, the energy has gone from the first into the second marble, which is gradually expending it in the work of overcoming the resistance of the floor on which it rolls.

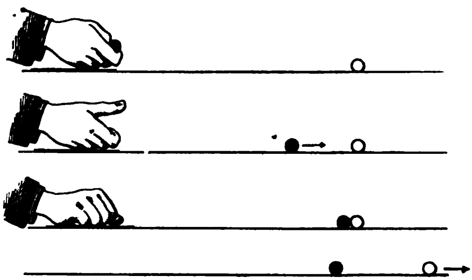

Fig. 20.

Likewise in every case when work is done, energy is *transferred* from the agent which does it to that on which it is done.

c. We are to look upon energy as a *real thing* which can and does actually go out of one body into another when work is done, and which then remains stored in the other until, in turn, the other expends it in doing work. The following illustration should help to make this conception clear:

Let a toy pail containing sand be lifted by pulling a cord which reaches from the pail over a grooved wheel, as shown in Fig. 21, A. Then fix the end of the cord upon a hook, as shown in B. Where is the energy which the hand expended in the work it did in lifting the pail? You can find it in the lifted pail. To do so, let the end of the cord be taken from the hook and fastened to a second pail, just a little lighter than the first, as shown in C. The first pail will then lift the second to the same height that it had itself been lifted by the hand, as shown in D. Where did it get the energy to do this work?

It received it from the hand (A). It held it stored within itself, while it remained suspended (B). And then it expended it in the work of lifting the second pail. Where is it now? Stored up in the lifted pail (D). The whole of it? Not quite, because a small part has been expended to turn the wheel. Except this small part which has passed into the apparatus, the lifted pail contains the energy that was expended by the hand in the first place.

d. Now notice that it was while the hand was *in motion* (Fig. 21, A) that it expended its energy. Also that the pail *while in motion* (C) expended the energy received from the hand. The energy which is actually being expended by any body in motion is called *kinetic energy.*

e. Notice, again, that the pail (B) *at rest,* after having been lifted, contains the energy given it by the hand. Also that

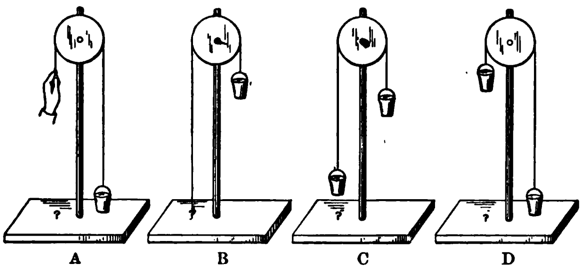

Fig. 21.

the other pail (D), *at rest* in its higher position, contains the energy which it received while going up. These bodies at rest are not doing work, but they contain the energy which was expended to lift them. The energy which is stored in bodies not doing work is called *potential energy.*

f. Energy cannot be measured directly; but it can be measured indirectly by the work which it does, and the units of energy are the same as those of work.

For example: If I lift a package whose mass is 25 pounds

from the floor to the top of a table 3 feet high, I expend 25×3, or 75, foot-pounds of energy.

If a body is put in motion by a force of 1000 dynes, and goes a distance of 20 cm., the energy expended is 20,000 ergs (§ 15, *b*).

g. A large mass of rock, rolling down a mountain, overcomes all obstacles, and we know that its energy increases with its speed. A bullet from a gun pierces or shatters an obstacle, but its energy would be still greater if its mass were larger. In fact the kinetic energy of a body depends on both its mass and its speed.

h. To find the kinetic energy of a body in motion, its mass must be multiplied by one half the square of its speed. For example: Suppose a 15-pound ball is moving at a given moment with a speed of 60 feet per second. Its kinetic energy, — that is to say, the energy it could expend, if suddenly stopped by another body, — is $15 \times 60^2 \div 2$, or 27,000, foot-poundals.

The operation may be represented by the equation:

$$\text{Energy} = \text{mass} \times \text{speed}^2 \div 2.$$

Or more briefly, by using letters in place of words:

$$E = \tfrac{1}{2} M \times v^2.$$

Example. — 10 kg. of rock is tumbling down a declivity, with speed, at a given moment, of 1.5 m. per second. What is its kinetic energy at that moment, in ergs?

The mass being 10,000 g. and the speed 150 cm., we have

$$E = \tfrac{1}{2} M \times v^2 = \tfrac{1}{2} \times 10{,}000 \times 150^2 = 112{,}500{,}000 \text{ ergs}.$$

i. That this method is correct may be shown as follows: We have seen that a force is measured by the product of the mass moved by it and the acceleration it imparts (§ 12, *b*). So, using letters for words, we have for the force involved in the motion of a body,

$$F = M \times a. \qquad (1)$$

But the work done by it (§15, *a*) is

$$W = F \times s.^{1} \qquad (2)$$

It is proved [§ 56, *e* (3)] that

$$s = \frac{v^2}{2a}. \qquad (3)$$

Now for F in equation (2) put its value $M \times a$, and for s, its value $\frac{v^2}{2a}$, and equation (2) becomes

$$W = Ma \times \frac{v^2}{2a}.$$

Or, canceling a, $$W = M \times \frac{v^2}{2}, \text{ or } \tfrac{1}{2} Mv^2.$$

As W stands for the work, — all the work possible for the moving body to do, — it represents the *kinetic energy* in the body. So we prove that *the kinetic energy in a moving body is one half the product of its mass by the square of its speed.*

j. The absolute unit, or erg, is a very small quantity of energy, and requires the use of very large numbers to express ordinary values. On this account larger units are used. These are multiples of the erg. Thus:

1 kilerg = 1000 ergs.

1 megerg = 1,000,000 ergs.

For example: The energy found in the foregoing example (p. 46), 112,500,000 ergs, may be given as 112.5 megergs.

18. **The Conservation of Energy.** — *a.* Experiments in great number, and of the most refined character, have proved that there is never any destruction of energy. The most that can take place is a transfer of energy from one body to another. It leaves a body which does work; it enters other bodies on which the work is done. At one time it is exhibited in one kind of work; at another time the same energy is exhibited

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[1] s is generally used to represent the *distance* traversed by a moving body, and v to represent the speed, or velocity. They are so used here.

in a very different kind of work. It is differently distributed among bodies at different times, but the sum total in all bodies is not changed.

b. The law of conservation of energy states that *the energy in any system of bodies may be differently distributed and appear and reappear in different kinds of work, but in all its changes there is neither loss nor gain in quantity.*

In the *physical* universe, matter and energy are the only things whose quantity cannot change.

19. Studies. — 1. If a 30-pound cannon ball leave the cannon with a velocity of 1500 feet per second, what is its momentum?

2. What is the kinetic energy in the ball mentioned in the preceding problem, at the moment when it leaves the gun?

3. Suppose that the same ball mentioned in the foregoing problems, after having gone so far that its velocity is reduced to 1400 feet per second, strikes a wall; what is its kinetic energy at that moment?

4. How can you account for the loss of energy from the ball on its way from the gun to the wall?

5. If the mass of a hammer is 150 g., and it strike a nail with a velocity of 40 cm. per second, how far will it drive a nail into wood which offers a constant resistance equal to 1000 ergs per .1 mm.?

6. How much work can a 4 horse-power steam engine do in one hour?

7. Assume that a gallon of water is 8 pounds, and suppose that 100,000 gallons must be forced up a vertical pipe to the height of 75 feet daily, by a steam engine working five hours per day. What horse-power would be required of the engine?

8. What horse-power would be required to run an elevator, the mass of which, when loaded, is 2000 pounds, to the top of a 60-foot building at a speed of 2 feet per second?

9. Work consists in putting matter in motion, or in changing the speed or the direction of matter already in motion, or in keeping up motion against friction or some other resistance. Now suppose you hold a dumb-bell motionless in the hand at arm's length; are you doing any work? Suppose you carry the dumb-bell in a straight line horizontally with perfectly uniform speed; are you then doing any work? The earth is moving on its axis with enormous but uniform velocity; is it doing any work? Would it be able to do work if it were to rub against another planet? Does it contain energy, either kinetic or potential?

THE TRANSFERENCE OF ENERGY.

20. **Media.** — *a.* The question now arises: How is the transfer of energy accomplished? We must consider three cases:

1. When two bodies touch each other directly.
2. When a third body between touches both.
3. When they do not touch each other and no tangible substance exists between them.

b. When bodies touch each other, energy may pass directly from one to another at the points of contact, as when the bat strikes a ball. When two bodies are separated by a third which touches both, energy may pass through the third, entering and leaving at the points of contact. For example: The energy of the hand (Fig. 22), by passing through the cord, moves the ball.

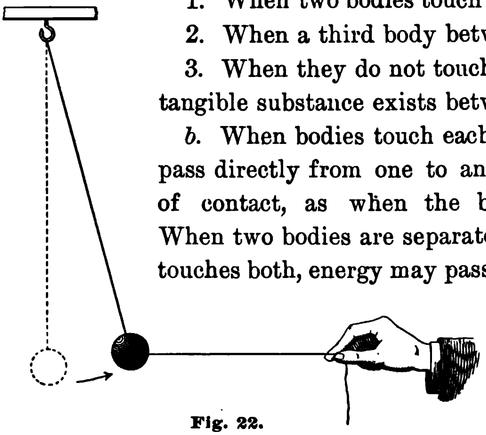

Fig. 22.

But if there is no material thing between, to carry the energy, it is not easy to see how it can be transferred from one body to another. Yet such cases are numerous. One such case is found in the following experiment:

Experiment 13. — A magnetic needle NS (Fig. 23) usually points north and south, when at rest. But bring the south end of a magnet to within a few inches of the north end of the needle, and that end will swing toward the magnet.

A mutual action between the magnet and needle is evident, but how is it transmitted? Not by the air, *nor by any other kind of ordinary matter*, since the result is the same when the experiment is made in a vacuum.

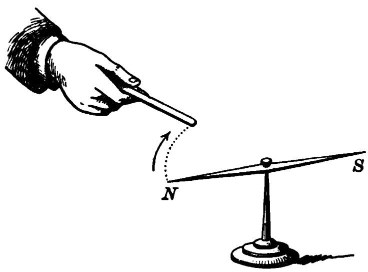

Fig. 23.

c. In such cases energy must be transferred in one of two ways: It must leap from one body to the other through empty space, or it must be carried by something in space which we cannot see or otherwise detect. The latter view is the one generally accepted.

For the transmission of energy through what seems to be empty space, there is supposed to be a medium which we can not detect by any of the usual tests for matter. It is called *ether.* This intangible substance is supposed to fill all spaces which are not actually occupied by ordinary forms of matter. It is believed to fill all the little spaces between the minute particles of which all bodies consist, and also the vast spaces between the earth and sun and stars.

21. **Attraction and Repulsion.**—*a.* By the *mutual action* of bodies when nothing but the ether exists between them, they are sometimes pulled nearer together and sometimes pushed further apart.

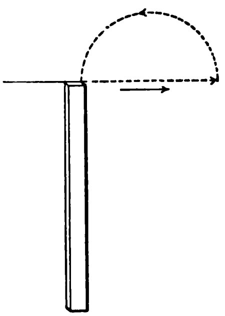

Fig. 24.

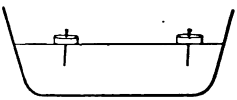

Fig. 25.

Experiment 14.—Select two needles about two inches long. Magnetize them by drawing each one along, *from point to eye,* point foremost, across one end of a magnet (Fig. 24) four or five times, carrying it back each time in the arc of a circle. Thrust each needle through a thin cork; place them a little distance apart on the surface of water (Fig. 25) with both points down. Each will appear to drive the other away. Repeat, to see whether the separation may not have been accidental. Then turn one point up, and repeat the experiment. Each will seem to pull the other toward itself.

That these motions are due to nothing but the mutual action of the two needles is proved by the fact that they will occur in a vacuum, showing that the air has nothing to do with it, while the water used in the experiment serves only to float the needles so that they can move easily.

The mutual action of bodies by which they are drawn toward each other is called *attraction.* The mutual action of bodies

by which they are pushed away from each other is called *repulsion.*

b. It is customary to speak of attraction or repulsion as if it were exerted by one of the bodies only, as when it is said that an apple falls from a tree because it is attracted by the earth. In so doing we speak a half truth. We neglect the fact that the apple attracts the earth no less than it is attracted by the earth. No harm results from this if only we know that we are doing so. It is also customary to speak of *forces acting* upon bodies. This, too, is more convenient than accurate. Bodies act upon one another, and forces are simply their mutual actions.

22. **Stress and Strain.**—*a.* But a medium is itself affected by the energy or the force which it transmits from one body to another.

In what condition is the rope, for example (Fig. 13), while transmitting the force? In what condition is the pole of the car (Fig. 15) while transmitting the energy?

In the rope every particle is pulled both ways at once, and in the pole every particle is pushed both ways at once. There is action and reaction (§ 9, *d*) at every point in these media which connect the bodies. So there must be in every medium, whether it be ordinary matter or ether, an action and reaction at every point between the bodies. To designate the force which is in a medium, the word *stress* is used. Stress is an action and reaction at every point in a medium which transmits the mutual action of bodies.

For example: A carriage is drawn by horses. The horses *act* against the carriage; the carriage *reacts* against the horses; and there is *stress* in the harness which connects the two. Numerous other examples can be cited readily.

b. Stress, having the nature of force, should be measured in dynes or poundals. For example: If the pull by a horse attached to a truck is 10,000 poundals, then the stress in

the harness is 10,000 poundals. This would be the *total stress.* But stress is defined more precisely as follows:

STRESS *is the number of units of force in one unit of area in a cross section of the medium.*

Thus the rope by which a horse draws a truck may be 1.5 inches in diameter. In that case it would have a cross section of 1.77 square inches, and the stress would be 10,000 ÷ 1.77, or 5649.7, poundals per square inch.

$$\text{Stress} = \text{force} \div \text{area of cross section.}$$

c. But media are elastic, and yield more or less to the force of the bodies acting through them. They are compressed by a push, expanded by a pull, and are said to be *strained.*

STRAIN *is any change in the length, the size, or the shape of a body which is subject to a stress.*

23. **Experiments on Work.**—*a.* If a body is to be lifted a little way, the work may be done by means of a bar and support (§ 24, *a*). In this way one can raise a mass which is many times heavier than he can lift by laying direct hold upon it. He does his work on the bar, and the bar lifts the body. The bar seems to increase his energy.

Experiment 15. — *Object.* To ascertain whether the work done *on* a bar which is used to lift a body is equal to the work done *by* the bar.

Apparatus. — In Fig. 26, *AB* represents a meter bar pivoted at its middle division, *F*.[1] It vibrates up and down very freely, but should rest in a horizontal position when its motion ceases. If it is not so nicely balanced, a little "rider," *C*, — a piece of tin bent neatly to fit the edge of the bar snugly, — is hung at the right place to balance it, and kept there. A scale pan, *P*,[2] with its load, is the body to be lifted, and another scale

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[1] To pivot the bar, a hole just large enough to take a slender wire nail and hold it firmly, is drilled through the bar at its 50 cm. division, and on a line with the ends of the millimeter marks. The bar is put between two screw-eyes in the support *S*, and the wire nail is pushed through them and the hole in the bar. With such a pivot there is no serious friction.

[2] Small round "baking tins" (3 inches in diameter) make excellent scale pans. Three small holes in the edge take the ends of three threads which terminate in a single strand, forming a loop to slide along the bar.

pan, *p*, with its load, is the body whose weight is the force to lift it. When the bar is horizontal, the bottom of the pans should be about 5 cm. above the table.

Operations. The mass of each scale pan must be known; weigh the pans if it is not given. Hang one pan, *P*, at 20 cm. from the pivot; add 50 g., and denote the mass of both by *M*. Hang the other pan at 35 cm.

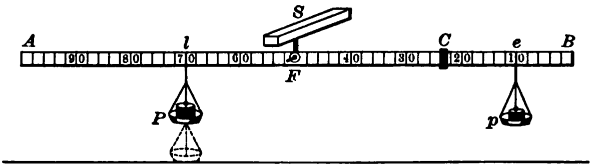

Fig. 26.

from the pivot, on the other side, add box masses until the bar becomes horizontal, and denote the total mass by *F*. Next measure the distances through which the forces work. To do this, let *P* down to the table by taking a mass from *p*, and find the height of the top of the bar above the table at each loop, *l* and *e*. Restore the mass to *p*, lift *M*, until *p* is on the table, and again measure the vertical heights of the tops of the loops. The difference between the two heights of *p* is the distance through which *F* works on the bar; call it *D*. The difference between the two heights of *P* is the distance through which the bar works on *M*. Tabulate the results:

Observations.				Computations.	
M	*F*	*d*	*D*	Work by *F*. $F \times D$	Work on *M*. $M \times d$
.... g.	.... g.	....cm.	....cm.	.... g. cm.	.... g. cm.

Repeat the observations by placing *P* at another distance from *F*, or changing its mass, and changing *p* accordingly. If the experiment has been well made, the work done *by F* and that done *on M* will be *nearly* equal. A small difference in the two results is accounted for by the friction of the pivot, and the fact that the measurements cannot be made exactly. (Appendix II., 4, *b*.)

b. If a body is to be lifted, the work may be done by means of an inclined plane (§ 27, *a*). The plane seems to increase the energy which is applied.

Experiment 16. — *Object.* To ascertain whether the work done by means of an inclined plane is equal to the work which would be done to lift the same body vertically to the same height.

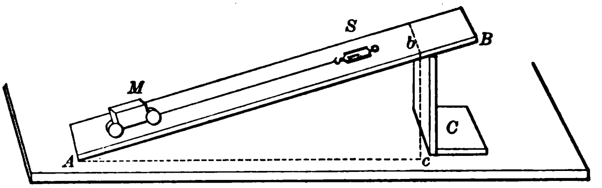

Fig. 27.

Apparatus. In Fig. 27, *AB* represents the inclined plane. It is a smooth board about 2 feet long, and 4 inches wide, with one end on the table and the other resting on a support. *M* is a Hall's carriage, and *S* a spring balance attached. The carriage and its contents are the mass to be raised from the table to the height *cb*, by pulling it up the plane.

Operations. — The mass of the carriage must be known; find it if it is not given. Add 50 g., and denote the mass of both by *M*. Draw *M* up the plane with a steady pull to some point, *b*, and note the reading of the balance during its progress. Then relax the pull until it is just strong enough to allow *M* to roll slowly down. If there is any difference in the two readings, take the mean, and denote it by *F*. *F* represents the force which would do the work if there were no friction. Measure the distance *AB* along the *under side* of the bar (why?). Denote this length of the plane by *L*. Measure the vertical height of the plane, from *c* up to the under side of the bar. It is the height to which *M* is lifted from the table. Denote it by *H*. Tabulate the observations:

Observations.				Computations.	
M	*F*	*L*	*H*	Work up the Plane. $F \times L$	Work up *cb*. $M \times H$
.... g.	.... g.	... cm.	....cm.	.... g. cm.	.... g. cm.

Change the value of *M* or change the inclination of the plane, and repeat the observations.

If the experiment has been well made, the work done along the plane and that which would be done to lift *M* vertically to the same height, are *nearly* equal in each case; not quite equal, because some work is wasted on the friction of the carriage. (Appendix II., 4, *c*.)

c. When work is done by means of any instrument, some part of it is wasted on the inevitable friction and other incidental resistances; but

The total work done ON *any instrument is just equal to the total work which can be done* BY *the instrument.*

Let this principle be remembered as the *principle of work.* It may be written in symbols, thus:

$$M \times d = F \times D; \text{ in which}$$

M stands for the resistance to be overcome;
F for the force which does the work;
d for the distance through which work on M is done;
D for the distance through which F acts to do it.

SIMPLE MACHINES.

24. **Machines.** — *a*. A machine is an instrument by which energy can be advantageously used to do work. For example: One end of a block of stone is to be lifted, and a strong bar is used for the purpose (Fig. 28). One end of the bar is inserted beneath the stone; a prop (F) is put under the bar near the stone, and the workman pushes the other end down. The bar transfers the energy from his hands, and expends it to raise the stone, whose mass may be many times greater than he could lift directly. The bar and prop are a machine.

Fig. 28.

b. There are three forces involved in the action of every machine. One is the force applied to do the work; another is the resistance offered by the machine itself on account of the friction of its parts, and other causes; and a third is the resistance which the machine is intended to overcome, such as that of a mass to be lifted.

c. The work required to overcome the resistance of the machine itself is wasted. Only that which is done to overcome the resistance to which the machine is applied is *useful.* Hence, *no energy is ever gained by the use of a machine, but some is always lost.*

d. To find the *total* work done on a machine, the *force,* in foot-pounds or other units, is to be multiplied by the *distance* through which its point of application to the machine moves.

The *useful* part of the work done by the machine is found by multiplying the *resistance* by the *distance* traversed by its point of application to the machine (§ 14, *b*). No general rule is given by which to find the wasted work.

We may state these rules by symbols, thus:

Let F stand for the working force, and D for the distance through which it moves its point of application. And let M stand for the resistance, and d for the distance through which its point of application moves. Then,

$F \times D =$ work done by the working force on the machine.
$M \times d =$ work done by the machine on the resistance.

If, now, we let w stand for the wasted work, we have, by the "principle of work" (§ 23, *c*),

$$F \times D = M \times d + w.$$

e. The more nearly perfect a machine is, the less is the wasted work, and in an ideal machine the wasted work would be nothing; w would drop out of our computations. For an ideal machine we have simply:

$$F \times D = M \times d;$$

which is a shorthand statement of the following law:

When work is done by the aid of a machine, the product of the working force by the distance through which its point of application moves, is equal to the product of the resistance by the distance through which its point of application moves.

This is the universal law of machines.

f. The wasted work varies with each machine. In the study of machines, they are regarded as perfect, and then in applying the results to practice, allowance is made in each case. The wasted work should be added to one or the other of the products, according as the resistance in the machine itself helps the working force, F, or the resistance, M.

What we have called the "working force" is generally called "the power," and denoted by P, and the resistance, M, is generally called "the weight," and denoted by W.

g. Machines are often very complicated in structure, but the most complex is made up of a small number of simpler ones. In fact, there are six simple machines, and all other machines are combinations of these. These simple machines are named as follows: lever, pulley, wheel and axle, inclined plane, screw, wedge.

25. **The Lever.** — *a.* A lever is a machine consisting of a rigid bar which may turn freely about a fixed axis. Any equivalent of such a bar, without regard to shape, is a lever. Fig. 28 represents a lever in use. In Experiment 15, the bar AB was a lever.

The fixed axis, represented in the figures by F, is called the *fulcrum.* The parts of a lever which lie between the fulcrum and the points of application of the power and the weight, are called the *arms.* In Fig. 26, Fe and Fl are the lever arms.

b. There are *three classes* of levers designated by numbers. In levers of the *first class,* the fulcrum is between the points

of application of the power and weight, as shown in Figs. 26 and 28. In levers of the *second class*, the point of application of the weight is between the fulcrum and the point of application of the power, as shown in Figs. 29 and 30. In levers of the *third class*, the point of application of the power is between the fulcrum and the point of application of the weight, as shown in Fig. 31.

c. The problem in the study of levers is this: To find the relative values of the power and the weight when they are able to just balance each other. But when they balance each other, no motion occurs, and the principle of work (§ 23, *c*; § 24, *e*) cannot be directly applied. We may, however, use the lengths of the lever arms instead of the distances through which the power and the weight move, because they have the same ratio. This simplifies the operation, since the arms can be directly measured. And with this substitution of lever arms for distances, the law of machines (§ 24, *e*) becomes the following *law of equilibrium* of the lever:

The power and weight will balance each other on a lever when, if each be multiplied by the perpendicular distance of its point of application from the fulcrum, the products are equal.

Example. — Suppose the straight bar lever in Fig. 28 is to be used to lift a stone whose mass is 1000 pounds, and let the fulcrum, *F*, be 1 foot from its bearing against the stone, while the workman's energy is applied at a distance of 10 feet from the fulcrum; how much force does he exert in order to just balance the stone?

The power arm is 10 feet, the weight arm is 1 foot, the weight is the weight of 1000 pounds, and the power is the workman's force. From the law of equilibrium we have:

$$\text{workman's force} \times 10 = \text{weight of 1000 lbs.} \times 1;$$

$$\text{workman's force} = \frac{\text{weight of 1000 lbs.}}{10} = \text{weight of 100 pounds.}$$

d. The *ratio* of weight to power in any simple machine is called the *mechanical advantage* of the machine. Thus the mechanical advantage of the lever in the example above is $\frac{10}{1}$;

in other words, any power applied to that lever will balance a resistance tenfold greater than itself.

Example. — If the power arm of a lever is 75 cm. and the weight arm 6 cm., what is the mechanical advantage of the lever?

26. **Lever Studies.** — *a.* In the beam balance (Fig. 10), the beam is a lever with its fulcrum midway between the points of application of the power and weight.

Experiment 17. — *Object.* To weigh a body by means of a lever pivoted at the middle point of its length.

Set up the apparatus represented by Fig. 26, with the addition of the index *I* (Fig. 30) to show when the bar is horizontal. Counterpoise the bar nicely, by means of its rider, *C*. Hang the two scale pans at *equal distances* on opposite sides of the pivot, and counterpoise the bar and pans by means of sand. Put the body whose mass is to be found in one pan, and then box masses in the other until the bar is horizontal. Record the following values:

Distance from the pivot to the loop of each scale pan .	—— cm. . . .	*D*.
Sum of the box masses used	—— g. . . .	*P*.
And represent the mass to be found by	. . .	*M*.

Then from the law of equilibrium of the lever (§ 25, *c*)

$$M \times D = P \times D. \quad \therefore M = P.$$

Conclusion. The mass of —— is —— g.

Could you find the mass of the body by this lever if the loops of the pans were not equally distant from the pivot? Try it, and describe and explain the process.

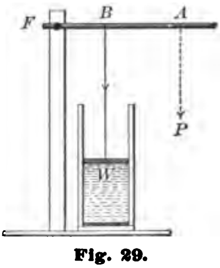

Fig. 29.

b. In the press represented by Fig. 29, a lever, *ABF*, with its fulcrum, *F*, *near one end* is used. The power is applied near the other end, *A*, for the purpose of compressing a substance beneath the piston at *W*. The reaction of this substance is the weight; its point of application is *B*. The problem: To find the mechanical advantage of this lever, if *FB* is 10 inches and *FA* is 35 inches.

The Computation. — By the law of equilibrium (§ 25, *c*),

we have $$P \times FA = W \times FB.$$

Hence $$P \times 35 = W \times 10;$$

and $$\frac{W}{P} = \frac{35}{10} = 3.5.$$

The mechanical advantage of this lever is 3.5. In other words, the pressure of W is 3.5 times the pressure applied at A; so that the weight of 100 pounds on the lever at A would bring a pressure equal to the weight of 350 pounds on W.

Experiment 18. — *Object.* To find by experiment the mechanical advantage of a lever of the second class.

For the lever use the bar shown in Fig. 26. Let it be pivoted in the same way, but near one end, as shown by Fig. 30, instead of in the

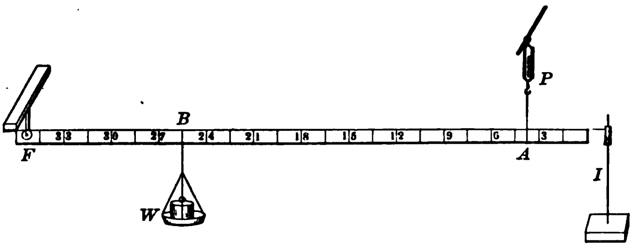

Fig. 30.

middle. A scale pan and its load may be the weight, and the upward pull of a spring balance may be the power. The balance may be supported by the clamp arm of a retort stand. Measure distances from the fulcrum by the English units, and remember that the lever arms are always to be measured *when perpendicular to the directions of the P and the W;* in this case, when *the bar is horizontal.* To see when the bar is horizontal, an index, *I*, may be used. It is a headless pin projecting from a cork, which may be fixed at any height on an upright wire. First adjust the pin to the height of the top of the bar at the fulcrum *F*, then place it at the opposite end.

Operations. Having set up the apparatus, without the scale pan, put the loop A at 35 inches from F. Adjust the height of the balance so that when its string is vertical the bar is horizontal, and read the scale. Denote this reading w; it represents the work wasted in lifting the lever

itself. Hang the pan W at 10 inches (d) from F; replace loop A at 35 inches (D); add known masses to the pan whose mass is likewise known or must be found; denote the total mass by W. Adjust the balance again and take the reading of its scale. Denote this reading p. The mass of W should be as large as practicable, so that the error due to the fact that the least count of the balance is quite large will not be so great in proportion to the weight. Tabulate the observations thus:

Observations.						Computations.		
Trial.	w	p	W	d	D	$p - w = P$	$\frac{W}{P}$	Error.
1	....	....	....	10″	35″	......	......	......
2	....	....	....	"	"	......	......	......

Repeat, using a different weight, W, each time.

The Error. The true value of $\frac{W}{P}$ is that which the law (§ 25, *c*, *d*) requires. Compute it (§ 26, *b*) and subtract the mechanical advantage, $\frac{W}{P}$, found by experiment. The difference is the *total error* of the experiment. If this error is a small fraction of the computed value, your experiment was well made. Thus: One student found the mechanical advantage of a lever to be 4.4, while its true or computed value was 4.25. The *total error* of his experiment was .15. But .15 is 3.5 *per cent of the true value* $\left(\frac{.15}{4.25} \times 100 = 3.5\right)$, and this was the error of that experiment. As he found a value *larger* than the true value, the error was + 3.5 %.

c. In Fig. 31, the treadle represented by FB is a lever. The resistance of the wheel to be turned is the weight, and the power is usually the pressure of a foot at A. This is a lever of the *third class*, because the power is applied at a point between the fulcrum and the point of application of the weight.

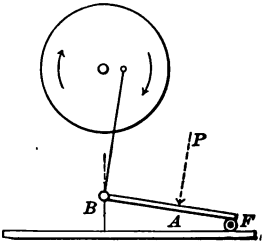

Fig. 31.

Let this lever be of the same length as the lever of the

press (Fig. 29), but let FA, instead of FB, be 10 inches, and FB be 35 inches. Compute its mechanical advantage.

Experiment 19. — *Object.* To find by experiment the mechanical advantage of the treadle (Fig. 31), or a lever of the third class.

Use the apparatus (Fig. 30) and follow the directions for the preceding experiment, except that you are to suspend the weight at 35 inches, and loop the balance at 10 inches, from F.

Compute the error of your experiment as explained above.

d. Fig. 32 represents a common pump. The pump handle, AFB, is a *bent lever*, with the fulcrum between the points of application, A and B, of the power and the weight. The power is the hand pressure at A in the direction of the arrow. The weight, W, is the weight of the piston and the water above it. The *directions* of the power and weight are not perpendicular to the lever as the law (§ 25, *c*) requires, and we must suppose that they are applied to the ends of straight arms, Fa and Fb, to which they would be perpendicular. In all cases, *the lengths of the lever arms are distances from the fulcrum in lines perpendicular to the directions of the power and weight.*

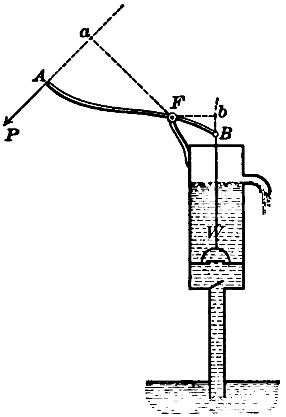

Fig. 32.

Example. — Let Fa be 2 feet and Fb 6 inches; what is the mechanical advantage of the pump? What is the greatest *mass* (of water and piston) that could be lifted by a pressure at A equal to the weight of 15 pounds?

e. Levers are not always in the form of rods or bars. Levers in the form of wheels are very common; they are known as *pulleys*, and *wheel and axles*.

f. A pulley is a grooved wheel free to turn on an axis. For example: Fig. 33 represents, in section, a wheel hung from a bar and free to rotate on its axis, F. A rope lies in the groove

around the wheel, and the power is applied at one end to lift a mass, *M*, at the other end. Now the power works upon the wheel at *A*, and the weight at *B*, the opposite ends of a diameter. So far as mechanical advantage is concerned, a simple bar, *AFB*, would be equivalent to the wheel, and this would be a lever. The wheel or pulley is equivalent to a lever, *AB*, with its fulcrum at *F*. It is *a lever with equal arms.* What is the mechanical advantage in this case? Remembering that there is some wasted work due to friction in the pulley, show that there is actually a *mechanical disadvantage.* But a person can do work more easily by pulling downward than by lifting, and in many other cases it is necessary to change the direction of the force applied. To offset the mechanical disadvantage in the use of a fixed pulley there is the *practical advantage* of a change in the direction in which the work may be done.

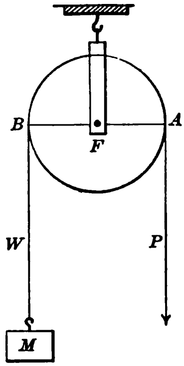

Fig. 33.

g. Besides the fixed pulley just described there is the *movable pulley,*—a wheel which is attached to, and moves with, the weight. It is a pulley whose axis is movable. The wheel represented by *H* (Fig. 34) is a movable pulley. It is generally used in connection with a fixed pulley, as shown. The cord, fixed at one end, *D*, passes under the wheel and then over a fixed pulley, *I*. A mass, *M*, is to be lifted by a downward pull at *P*. The pulley and the mass, *M*, together constitute the weight for the fixed pulley, *I*. Evidently the diameter of *H* is a lever (of which class?) with its fulcrum at *F*, the power working at *a* and the

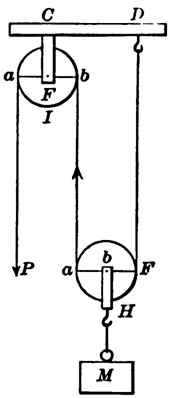

Fig. 34.

weight at *b*. Suppose the diameter, *aF*, to be 10 inches, and the mass, *M*, to be 100 pounds; how much power must be applied at *a* to balance *M* (§ 25, *c*)? What is the mechanical advantage of the pulley *H*? How much power must be applied at *P* to hold *M* in equilibrium? What is the mechanical advantage of the combination? In what does the waste work consist? The student may consult reference books to learn of different combinations of pulleys and their uses.

Experiment 20. — *Object.* To find the *practical* mechanical advantage of a movable pulley.

Having two pulleys, a cord, and two spring balances, proceed to hang the pulleys, as shown in Fig. 34. In place of *M* put a spring balance, and fasten its hook to something below, so that the balance cannot be actually lifted. Fix the other spring balance to the cord at *P*. Then pull the balance *P* vertically downward, thus lifting the pulley *H* and straining (§ 22, *c*) the balance *M*. Note the value of power shown by balance *P*, and of weight shown by balance *M*. Repeat with greater power, and obtain several sets of values. Then find the ratio of weight *M*, to power in each case. With good pulleys and careful work the results should not vary much. Take the average as the practical part of the mechanical advantage of one movable pulley. How far short of the theoretical advantage does it fall, and to what is the discrepancy due?

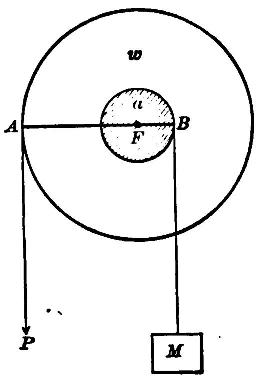

Fig. 35.

h. Fig. 35 represents, in section, a wheel, *w*, with a drum-shaped axle, *a*, projecting beyond its face, equivalent to a smaller wheel fastened to *w*. Such a combination of two wheels is called a *wheel and axle*. By applying a power, *P*, to the circumference of the wheel, a mass, *M*, on the end of a rope wound upon the axle, *a*, may be lifted. The figure shows that the wheel and axle is equivalent to a lever, *AFB*. The power arm is the radius, *AF*, of the wheel, while the weight arm is the radius, *FB*, of the axle. Suppose that the radius of the wheel is 3 feet, and of the axle

6 inches; what is the mechanical advantage? If the mass is 120 pounds, what power applied at P will balance it? How much further must the power fall than the weight rise, if motion occurs? Using the same wheel and axle, let a power equal to the weight of 100 pounds be applied *to the axle* at B; what weight would be balanced at A? How many times more rapid will be the motion of the weight than of the power in this case? Let the student consult reference books for the forms and uses of the wheel and axle.

27. **The Inclined Plane.** — *a.* When a teamster wishes to raise a heavy mass, such as a cask of sugar, from the ground to his cart, he does not attempt to lift it vertically, but he does the work by rolling the cask along a plank reaching obliquely from the ground up to the cart. The inclined surface of the plank is an inclined plane. Any rigid, sloping surface over which masses may be moved is an *inclined plane.*

b. In Fig. 36, ac represents an inclined plane. W is the weight, — a mass to be lifted from the ground to the height bc, by a power P, which pulls it along ac. While W is going from a to c, the power, P, at the other end of the rope, must go an equal distance, PP'. The power works through a distance equal to ac. But, at the same time, the mass W is lifted only through the height bc (§ 14, c). By the law of machines (§ 24, e),

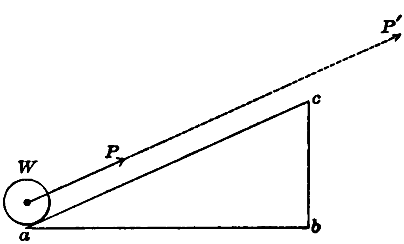

Fig. 36.

The work done by the power is power $\times\ ac$;
The work done on the weight is weight $\times\ bc$.

Hence, $$P \times ac = W \times bc.$$

From this equation we find the mechanical advantage (§ 25, *d*),

$$\frac{W}{P} = \frac{ac}{bc}, \text{ or } \frac{\text{length of the plane}}{\text{height of the plane}}.$$

Example. — Suppose the teamster's plank to be 12 feet long, and his cart 4 feet high. If a cask of sugar is 326 pounds, what power must he exert to push it up? In this case $\frac{ac}{ab} = \frac{12}{4}$ or $\frac{3}{1}$ = the mechanical advantage. That is, every 3 pounds to be lifted requires a power equal to the weight of 1 pound. To lift the cask requires 326 ÷ 3, or a power equal to the weight of 108⅔ pounds.

28. **Inclined Plane Studies.** — *a.* Suppose an inclined plane whose height is 6 feet and whose length is 15 feet, is used to lift 250 pounds; what power parallel to its length will be required?

b. But suppose the power is exerted *parallel to the base of the plane;* what power would then be required? First represent the plane (Fig. 37). Its base is *ab*, and its height is *bc*, *W* is the weight, and *P* the power, which is kept at work all the time parallel to *ab*, while the weight rises. When *W* has reached *c*, its *horizontal* distance is *ab;* how far *to the right* has *P* gone in the same time? To what distance has *W* been *lifted* in the same time? By the law of machines (§ 24, *e*),

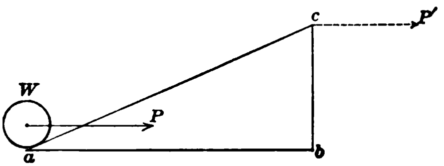

Fig. 37.

$$P \times ab = W \times bc.$$

From this equation find the mechanical advantage. Having the mechanical advantage, find what power would be needed to lift 100 pounds to the *height* of 10 feet by an inclined plane whose *base* is 18 feet. When the power works parallel to the length, as in § 27, *b*, what measurements of the inclined plane represent the working distances of the power and the weight?

When the power works parallel to the base of the plane, what measurements represent the working distances of the power and the weight?

c. If W (Fig. 38) is a massive ball on the end of a bar hinged at h, it could be lifted by pushing an inclined plane, abc, under it. Should the direction of the power be parallel to the base, ab, or to the length, ac, to do this work to the best advantage?

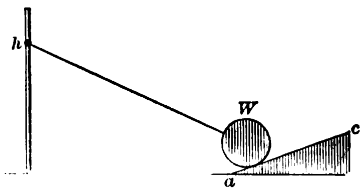

Fig. 38.

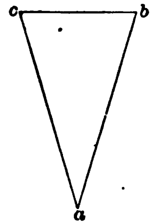

Fig. 39.

An inclined plane, when it is pushed or driven, as shown above, is called a *wedge.* But the wedge is usually made with both faces slanting (Fig. 39). In that case the wedge is really a double inclined plane, as you can see by drawing a line from a perpendicular to bc.

d. Examine the blade of a pocket knife, and while cutting a piece of wood, study its action as a wedge. What is the power, and what is the weight, and what is the work?

Examine a sewing needle and describe it as a wedge.

All cutting and piercing instruments are wedges.

e. Examine a common screw. Choosing one of large size, place its point in a dent made in a block of wood, and hold the screw upright. Press the sharp point of a lead pencil into the groove, near the point of the screw, and then turn the screw several times around. You should discover that the spiral ridge on the screw is an inclined plane *which is pushed under the pencil point* (compare *c*).

The projecting ridge around the body of a screw is called

the *thread*, and the end of the screw to which the power is applied is called the *head*. The distance measured parallel to the axis of the screw between two adjacent turns of the thread is called the *pitch* of the screw.

f. Fig. 40 represents a screw in use as a machine, to bring great pressure to bear upon books in the process of binding.

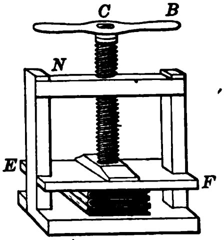

Fig. 40.

The screw works through the fixed block, *N*, called the *nut*. Its thread runs in a groove inside the nut, and its end rests upon a movable pressure board, *EF*. The power is applied to the end of the lever *BC*, and the weight is the resistance of the books placed under *EF*.

If the screw is driven down a distance equal to the pitch of the screw, the power distance is the circumference of the circle whose radius is *CB*. The law of machines gives

$$P \times \text{circ. } CB = W \times \text{pitch of the screw.}$$

From this equation we find the mechanical advantage of a screw:

$$\frac{W}{P} = \frac{\text{circ. } CB}{\text{pitch of screw}}.$$

Find what pressure would be exerted on the books (Fig. 40) by a power equal to the weight of 25 pounds at *B*, 2 feet from the center of the head, *C*, if the pitch of the screw is .25 inches.

29. **Summary of Laws of Equilibrium stated as Proportions.**[1]—*a.* In a lever: The power and weight are in equilibrium when $P : W :: \text{weight arm} : \text{power arm}$.

b. In a pulley: The power and weight are in equilibrium when $P : W :: 1 : \text{number of branches of rope which support the weight}$.

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[1] **The laws are the translations of the equations for the several machines as explained in Appendix II.**

c. In a wheel and axle: The power and weight are in equilibrium when $P:W::$ radius of axle : radius of wheel.

d. In an inclined plane, with power parallel to its length: The power and weight will be in equilibrium when $P:W::$ height of plane : length of plane; and with power parallel to base of the plane: $P:W::$ height of plane : base of the plane.

e. In a screw: The power and weight are in equilibrium when $P:W::$ pitch of screw : circ. of power circle.

f. In a wedge: The sharper the wedge, the greater is the mechanical advantage. No precise law of any practical value can be stated.

30. **Efficiency of Machines.** — We have seen that the mechanical advantage of a machine is a theoretical value; it takes no account of waste work. Practically, the work done on a machine must be much greater than that which is indicated by the mechanical advantage, as in the case of the movable pulley (§ 26, *g*), where a large fraction of the work actually done is required to lift the pulley itself.

What is more important to the engineer, is to know the ratio of the *useful work,* — that which he can actually do with the machine,—to the *total work* applied to the machine. The ratio of the *useful work* done by a machine, to the *total work* done on the machine, is called the *efficiency* of the machine. For example: If 1000 foot-pounds of work is done by the power used, and only 560 foot-pounds of useful work is obtained from it, the efficiency of the machine is $\frac{56000}{1000}$, or 56, *per cent.* Efficiency is stated as a certain percentage of the actual work done on the machine.

From the results obtained in Experiment 20, compute the efficiency of the movable pulley which you used.

III. STRUCTURE AND PROPERTIES OF MATTER.

THE STRUCTURE OF MATTER.

31. **Divisibility.** — *a.* Any body of matter may be cut or broken into pieces without in any way changing the character of its substance. The property of matter by virtue of which a body may be separated into parts, is called *divisibility.*

b. The process of division without changing the character of a substance may be carried so far that the number and minuteness of the pieces almost exhaust the power of imagination. A kernel of wheat when ground to finest flour is broken into pieces which cannot be separately seen by the naked eye. A fragment of stone may be crushed and ground until it becomes an impalpable powder; that is to say, a powder so fine that we feel no gritty sensation when it is rubbed between the fingers.

A cloud consists of particles of water floating in the atmosphere. The size of these particles in a light cloud has been estimated to be such that 13,000 placed side by side would measure only an inch in length.

About 300,000 sheets of ordinary gold leaf would together measure about an inch in thickness. If a square inch of one such leaf were reduced to powder, there would be about ninety thousand million particles of the gold dust.

The following experiment illustrates the extreme divisibility, and consequently the extreme minuteness, of particles of aniline red.

Experiment 21. — *Object.* To estimate the number of pieces into which 1 g. of aniline red can be divided, and the mass of each piece.

Crush a few small crystals of aniline red; weigh out .01 g. of the powder. Transfer it without loss to a graduated cylinder. Add a little alcohol to dissolve it, and then add water to fill the cylinder to the 20 cc. mark. After thoroughly mixing the red solution and water, pour just 1 cc. of it into a large glass jar, and then with a measuring glass add water, keeping careful count of the quantity, until the color is so diluted as to be just visible throughout the jar.

Now every drop of water in the jar must contain *at least* one little piece of the aniline red, in order to show color. If you can find the number of drops, you will have the least possible number of pieces, and then you can find the mass of one of them.

To estimate the number of drops: Fill the cylinder to its upper mark; press a wet stick or glass rod against its lip, and carefully tip the cylinder until drops slowly fall from the end of the stick. Count the drops until just 10 cc. have been discharged. Repeat, and take the average of two or more trials as the number of drops in 10 cc. From this you can find the number of drops contained in the jar.

In one experiment this number of drops was found to be	80,000
The original quantity of aniline in 20 cc. was	1 cg.
Hence the 1 cc. put into the jar contained	$\frac{1}{20}$ cg.
This was divided among	80,000 drops
Hence the number of pieces of the $\frac{1}{20}$ cg. not less than .	80,000
Total number of pieces of the 1 cg. not less than . . .	1,600,000
Hence total number of pieces of 1 g. not less than . . .	160,000,000
Mass of one of these pieces not more than	.000000006 g.

Every one of this multitude of minute pieces is a particle of aniline red. The character of the substance has not been changed by the division.

c. But there is a limit beyond which a body cannot be divided without changing its substance into two or more different kinds of matter.

When water boils it becomes steam, — invisible because it is divided into innumerable particles widely separated from one another. But these particles are the identical particles of the water before the heat was applied. If the steam is passed slowly through an iron tube containing iron filings, which are kept red hot, no steam will issue from the other end. Instead of steam, a gas may be collected which burns when touched

with a match flame. At the same time another substance is taken from the steam and held by the iron. The substance which burns is hydrogen; that which is held by the iron is oxygen. In this case every particle of steam is divided into particles of two entirely different kinds of matter.

d. But neither hydrogen nor oxygen has ever been separated into other kinds of matter. Such substances are called *elements.* Gold, iron, sulphur, and carbon are elements, because, like hydrogen and oxygen, they have never been broken into other kinds of matter. On the other hand, water and all other substances which have been broken into simpler kinds of matter are called *compounds.*

e. A particle of any substance, which cannot be divided without changing it into other kinds of matter, is called a *molecule.* All bodies are made up of such particles.

f. By dividing the molecules we obtain the still smaller particles of the different kinds of matter they contain. For example, the chemist tells us that every molecule of water contains two particles of hydrogen and one of oxygen. Such smallest particles of elements, or simple kinds of matter, are called *atoms.*

32. **Molecular Spaces.** — It has been said that two bodies can never occupy exactly the same space at the same time. We may now consider some facts which seem to contradict that statement.

a. If the edge of a sheet of blotting paper touches a drop of ink, that liquid enters the paper and remains therein. If one corner of a block of loaf sugar be made to touch the surface of water, it is quickly wetted throughout, even to its remotest parts. It would seem that there must be open spaces within the paper and the sugar, into which the liquids go.

b. Francis Bacon made the following experiment about three hundred years ago. He filled a lead shell with water, closed it completely, and then put it under pressure. The water

oozed out through the lead, and stood in beadlike drops on the oùtside surface. A silver shell was tried long afterward in Florence with the same result. When a silver shell coated with gold was used, it could not retain the water. Under pressure the molecules of water found a passage between the molecules of these compact metals.

c. Gold is one of the densest metals, and yet mercury, on contact with gold, is absorbed by it, as water is absorbed by a sponge.

Such facts confirm the belief that no body completely fills all the space which it appears to occupy. That property of matter by virtue of which there are unfilled spaces among the molecules is called *porosity.*

Experiment 22. — Fill a graduated cylinder with alcohol, to a certain mark exactly, perhaps the 50 cc. mark. Take cotton wool of fine quality, pull it out into slender shreds, bring these one after another into contact with the surface of the alcohol, and lower them into the liquid, assisting their descent by gently pushing them with a glass rod. Find how much of the cotton you can introduce, if any, without raising the level of the alcohol. See that no alcohol is lifted out on the glass rod. Point out the bearing of your result on the question of unfilled spaces in alcohol, and also in cotton fibers.

If you should fill the cylinder to the mark with shot could you not add a quantity of fine sand without lifting the surface above the mark? What would become of the sand?

In like manner try water and sugar. Having filled the cylinder to the mark with hot water, slowly sprinkle into it a measured quantity of powdered sugar. Is the apparent volume of the liquid increased? What has become of the sugar?

33. **Molecular Motion.** — For many reasons, which will better be given as our study advances, it is believed that the molecules of any body are never at rest, but are in ceaseless motion within the inconceivably small spaces around or between them.

34. **The Molecular Theory.** — The statements just made in regard to molecules, molecular spaces, and molecular motions, cover the views now held as to the structure of matter. *The molecular theory* states that every body is built up of minute

particles, called molecules, which cannot be divided without changing them into other kinds of matter. The molecules are surrounded by spaces which are filled only by ether, within which they are in rapid and ceaseless motion.

35. **Physics and Chemistry.** — Atoms are scarcely at all considered in the study of physics. Molecules and masses and the energy they exhibit in their physical changes are the chief subjects of study in this science.

In the science of chemistry, atoms and the different kinds of matter which they form when chemical changes occur, are the chief subjects of study.

SOLIDS, LIQUIDS, GASES.

36. **Rigidity.** — Among the many things in which a substance like iron differs from another like water, one of the most striking is this: A piece of iron will bear very great pressure without changing shape, while water will be distorted by any pressure however small.

A body whose form will not be changed by great pressure is said to be rigid. *Rigidity* is the property of matter by virtue of which it can resist a stress (§ 22, *a*). Bodies that possess this property in high degree are called *solids.*

37. **Fluidity.** — *a.* Many substances like water yield to the slightest pressure. They cannot resist the pressure due to their own weight; they can be kept in shape only by the reaction of the walls of the vessel in which they are placed; they will ooze in drops or streams from leaky vessels because they cannot bear the stress due to gravity; and they will be distorted by the gentlest push against their surfaces. *Fluidity* is the property of matter by virtue of which it cannot resist a stress. A body whose form will be changed by the gentlest pressure is called a *fluid.*

b. A perfect solid would be one whose rigidity would not

allow it to yield at all to the greatest possible stress. A perfect fluid would be one without any rigidity, — one which could not at all resist the slightest stress. But no such bodies are known. Practically, we may define solids and fluids in this way: A *solid* is a substance with such rigidity that the shape of any body of it will not change under the stress of its own weight. A *fluid* is a substance with so little rigidity that a body of it cannot keep its shape when left to the stress of its own weight.

c. When a body changes form continually under a stress, it is said to *flow*. All fluids flow, under the stress of their own weight, if they are not kept from doing so by some reaction, such as that of the walls of the vessel in which they are contained.

38. **Plasticity.** — It is well known that a piece of stiff putty, if laid upon the table, will maintain its shape against the stress due to its own weight; it is therefore practically a solid. But press upon it with the hand, and its shape will be changed, and if the hand is withdrawn, the putty will retain its new shape. A great many substances will thus change shape under sufficient stress, and retain the new shape when the stress ceases. Wet clay, wax, and red-hot iron are examples. They are said to be plastic. *Plasticity* is the property of matter by virtue of which bodies take new and permanent shapes under a temporary stress.

39. **Viscosity.** — *a*. Some substances, such as water and alcohol, flow very freely. Others, like treacle and pitch, flow, but with apparent reluctance; these are said to be viscid. *Viscosity* is the property of a fluid by virtue of which it resists the stress which causes it to flow.

b. A viscid fluid and a plastic solid seem to be much alike. Indeed, every substance which will flow, even in the least degree, is, to that degree, fluid. Many so-called solids, like sealing wax and ice, are viscid fluids. For example: Let a

stick of sealing wax — the longer the better — rest with its ends on supports above the table. After a day or two it will be found to be bent down in the middle. This bending will continue slowly so long as the middle part is not supported. The sealing wax yields continually under the stress of its own weight. It flows really, though slowly.

A plastic substance is one whose internal structure is weak enough to yield to pressure, but strong enough not to yield all at once. A viscid substance is one whose internal structure is so weak that it must yield to the pressure of its own weight, but strong enough not to yield all at once. In a fluid the internal structure is so weak that it must yield to the slightest pressure all at once. But if these substances are built up of molecules (§ 34), why should they have any strength at all? (§ 21, *a.*)

40. **Compressibility.** — *a.* It is well known that a rubber ball may be made smaller by pressure, without changing its mass. On this account rubber is said to be compressible. *Compressibility* is the property of matter by virtue of which a given mass becomes smaller under pressure.

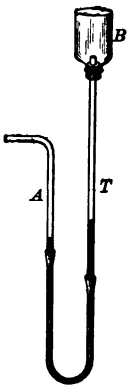

Fig. 41.

Experiment 23. — The compressibility of air by pressure may be tested as follows:

B represents a small bottle, and *T* a glass tube passing through a tightly fitting stopper. *A* represents another glass tube which is joined to the tube *T* by a rubber tube. Colored water fills the bend of the rubber tube and stands at a convenient height in *T*. The bottle and tube above the water are full of air, which cannot escape. Apply the lips to the tip of *A*, and gently press the breath into the tube. You will see the water rise in *T*, perhaps into the bottle, crowding the air into a smaller space.

b. Air is compressible in a very high degree. In this respect it differs very much from water. If a cubic inch of water were inclosed in a vessel with rigid walls, it would require enormous pressure to reduce its volume perceptibly. A pressure equal to the weight of 14.7 pounds per

square inch would reduce its volume by only .00005 of a cubic inch, while a cubic inch of air under the same pressure would be reduced by .5 of a cubic inch, or to one half its volume.

Thus substances possess the property of compressibility in very different degrees. The compressibility of all solids and liquids is slight in comparison with that of gases.

But if bodies are built up of molecules, how can they be made smaller by pressure?

41. **Expansibility.** — *a.* It is well known that an iron ball is larger when hot than when cold. Its mass remains the same, but its volume is increased by heat. If with the lips applied to the tube *A* (Fig. 41), the air above the water in *A* be sucked out, the water in *T* will fall. There will then be the same mass of air in the bottle and tube, but it will fill a larger space than before. The property of matter by virtue of which the volume of any given mass may be increased is called *expansibility*.

Experiment 24. — The expansibility of water by heat may be tested as follows:

A bottle or flask is provided with a tightly fitting stopper and a tall glass tube. Fill the flask with water to the brim. Press the stopper into the neck until it makes a tight joint. The water will rise in the tube as the stopper enters the neck of the flask; mark its height. Finally, place the flask in a vessel of almost boiling water. Watch for a rise of the water in the tube, and consider how this shows the expansibility of water.

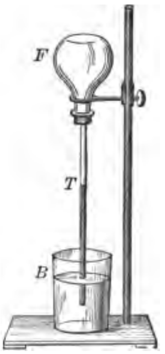

Fig. 42.

Experiment 25. — The expansibility of air by heat may be tested as follows:

A flask, *F* (Fig. 42), about the same size as that used in the preceding experiment, is provided with its tight-fitting stopper and long tube, *T*. Support the flask by a ring on the retort stand, with the end of *T* deep in a small vessel of water, *B*. Pour almost boiling water over the flask, and watch for bubbles in the vessel *B*. Allow the flask to become cold, watching, meantime, for a rise of water in *T*, and consider how the experiment has shown the expansion of air by rise of temperature, and also its *contraction* by fall of temperature.

b. The volume of a given mass of air changes greatly with changes in its temperature, and also with changes in the pressure which it sustains. The volume of a given mass of water changes very much less with changes in its temperature, and almost not at all with changes in the pressure.

c. The expansibility of many substances, such as alcohol, ether, and oil, is like that of water, while the expansibility of others, such as oxygen and hydrogen, is like that of air. Hence two classes of fluids are recognized. A fluid, the volume of a given mass of which is not perceptibly changed by changing the pressure upon it, is called a *liquid*. A fluid, the volume of a given mass of which is indefinitely increased by diminishing the pressure upon it, is called a *gas*.

SOME PROPERTIES OF SOLIDS.

42. **Hardness.** — *a*. It is well known that lead is easily scratched, even with the finger nail; copper is not. But copper is easily scratched by a knife blade; a piece of glass is not. These facts show that it is more difficult to rub away the particles of (that is to abrade) some substances than others. Substances not easily abraded are said to be hard. The property of a solid by virtue of which its substance is not easily worn away, or abraded, is called *hardness*.

b. Hardness does not imply strength. Glass is very hard, but it is also very fragile. Hardness does not imply density (§ 6, *a*). The diamond is the hardest of known substances, while gold is so soft that it may be easily scratched with a knife; yet the density of gold is almost six times that of diamond. Mercury is a liquid and has no hardness, but its density is about 1.75 times that of the hardest steel.

c. The hardness of some substances can be made greater or less by skillful application of heat. Steel, in its hardest condition, is too brittle to be much used in the arts, but by

heating it to different high temperatures, and then suddenly cooling it, the steel may be left with any degree of hardness desired. This process is called *tempering.*

d. When cooled very slowly from a high temperature, such as red heat, many substances become softer and less brittle. This process is called *annealing.* Glass when not annealed breaks down when slightly strained. This explains the fact that articles of glassware sometimes break without apparent provocation; they cannot bear the strain of a slight change of temperature. To be durable they must be well annealed.

43. **Malleability.** — Many substances, especially some metals, — notably iron, silver, and gold, — may be hammered, or pressed between rollers, into thin sheets. The property of a substance by virtue of which it can be reduced to thin sheets by blows, or heavy pressure between rollers, is called *malleability.*

44. **Ductility.** — *a.* Many substances, notably some metals among which are platinum, silver, and iron, can be drawn out into fine wire. The property which permits a substance to be drawn into the form of wire is called *ductility.*

Experiment 26. — The ductility of glass may be exhibited as follows: A soft glass tube, 8 or 10 inches long, $\frac{3}{16}$ of an inch in diameter, is represented at *T* (Fig. 43). It is held in the flame of a Bunsen burner, and constantly rolled in the flame to heat all sides equally. The glass will

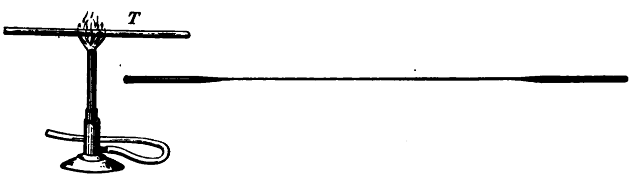

Fig. 43.

soften. When this occurs, it is taken from the flame, and, at the same instant, pulled lengthwise, with both hands. The heated part may be drawn out as far as the hands can separate; it will be a tube still, but perhaps smaller than a pin in diameter, and wonderfully flexible.

b. Ductility and malleability are closely related. That they

are two distinct properties is shown by the fact that the same metal may not be ductile and malleable in the same degree. Gold is the most malleable metal, but it stands below platinum, silver, iron, and copper in ductility. Platinum is the most ductile metal; it has been drawn into wires too small to be visible without a microscope.

c. In commerce the sizes of wires are specified by numbers. These numbers are found by means of an instrument called a *wire gauge* (Fig. 44). They are arbitrary, but they represent diameters. Thus a No. 1 wire, by a Brown and Sharpe wire gauge, is .7348 cm. in diameter, while a No. 30 wire has a diameter of only .0255 cm. The diameters corresponding to the numbers may be measured directly by means of a micrometer calliper, or found in tables. (Appendix III., 3.)

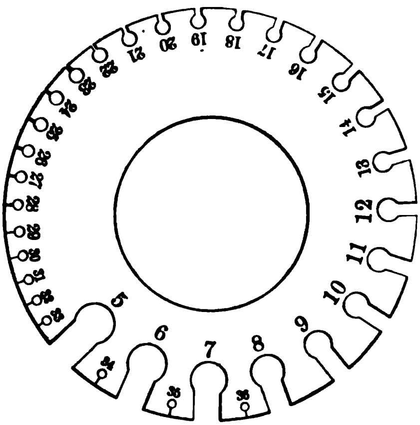

Fig. 44.

45. **Elasticity.** — *a.* A rubber ball when squeezed is reduced in size, but it recovers its former volume when the pressure is removed. A strip of steel after having been bent recovers its former shape, and if a thread or wire is twisted it will untwist when the twisting force is withdrawn. On account of their power to recover from the change produced by a force, these bodies are said to be *elastic.*

But if a body is built up of molecules, how can it recover its former size after compression? (§ 21, *a.*)

If a body yields to a stress, in any way, whether it is compressed or extended, or twisted or bent, it is said to be

deformed or *strained*. *Elasticity* is the property of matter by virtue of which a body recovers from a strain.

b. Strain is the change in the size or the shape of a body; stress is the force which produces the strain; and elasticity is the property which enables the body to recover from it.

Experiment 27. — The elasticity of India rubber may be studied as follows: In Fig. 45, *hk* represents a rubber cord suspended from a hook and carrying a scale pan at the other end. If a small mass, *m*, be placed in the pan, the cord will be stretched to a length *hn*. The elongation, *kn*, of the cord is the *strain*. The mutual pull of the mass, *m*, and the hook, *h*, is the *stress* which produces the strain; it is equal to the weight of *m*. If *m* be taken from the pan, the cord springs back to the length, *hk*, and the property which enables it to do so is *elasticity*.

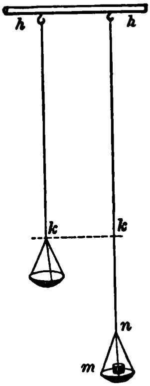

Fig. 45.

c. If a body recovers its original *size* after having been made smaller or larger by a stress, its elasticity is called *elasticity of volume*. Elasticity of volume is shown by a rubber ball, when it is released after it has been squeezed in the hand. If a body regain its original *shape*, as a strip of steel will do after having been bent, its elasticity is called *elasticity of form*.

d. A *perfectly elastic body* is one which completely recovers its original volume or shape the instant the stress is removed. Air and all gases, water and all liquids, are perfectly elastic. They recover their original size completely and at once when they are released from pressure, however great it may have been or however long it may have been applied.

e. But solids do not behave in this way. There is a limit to their elasticity. For example: If an iron wire is stretched by a moderate pull, it will spring back to its original length exactly; but if the pull is greater and greater, the wire will at length be stretched beyond its power to recover, and a permanent change in length will be produced. When this permanent

change, or "set," begins, the wire has reached the limit of its perfect elasticity. Very many solids are like iron in this respect. They are perfectly elastic so long as the stress does not exceed a certain amount. But if strained beyond their limit, they gradually lose elasticity and finally break (§ 46, *b*).

f. The elongation of any wire depends on three things: first, the length of the wire; second, the area of its cross section; and, third, the stretching force.

Take a unit value of each one of these three things, and the elongation is then called the *coefficient of elasticity* of the substance of the wire. Thus the coefficient of elasticity of iron is the elongation, per centimeter of its length, which results when a wire, whose cross section is 1 sq. mm., is stretched by the weight of 1 g. The kilogram is a better unit of stretching weight in case of very rigid substances like iron, because it gives a larger coefficient. Even then it is an extremely small fraction. But it is the same for all iron of the same quality. So, likewise, every elastic substance has its own coefficient of elasticity. The reciprocal of a coefficient, or $\frac{1}{\text{coefficient}}$, is called *Young's modulus of elasticity.* These values have been found with care, and are laid down in tables for the use of students and artisans. (Appendix III., 4.)

46. **Tenacity.** — *a.* A splinter of wood, which breaks easily when bent, cannot be broken easily by a pull directed lengthwise. A strip of paper, which is easily torn, is broken with difficulty by a steady pull in the direction of its length. Try it. The property of matter by virtue of which a body resists a tension is called *tenacity.*

b. If steel pianoforte wire is tested by fixing one end in a firm support above, while masses are hung upon the other end below, it is found that a wire whose diameter is only .2 cm. will sustain up to 740 kg. The force which is required to pull a body asunder is called its *breaking stress.* The weight

of 740 kg. is the breaking stress of the particular wire described.

c. The breaking force of a wire, or rod, or cord of any substance, whose cross section is a unit area, is the measure of the tenacity of that substance. Thus, for example: The tenacity of pianoforte steel is the weight of 235.5 kg. per sq. mm., because a wire of this steel, 1 sq. mm. area of cross section, requires the weight of 235.5 kg. to pull it asunder.

This value is found as follows: An experiment shows that the wire whose diameter is 2 mm. breaks under the weight of 740 kg. Now the area of the cross section, if the diameter is 2 mm., is $.7854 \times 2^2$, or 3.1416 sq. mm.; and if with this area it breaks under the weight of 740 kg. with an area of 1 sq. mm., it would break under the weight of $\frac{740}{3.1416}$, or 235.5, kg.

d. Hence the tenacity of a substance is found by dividing the breaking stress by the area of the cross section of the body broken. Thus:

$$\text{Tenacity} = \frac{\text{breaking stress}}{\text{area of cross section}}.$$

Tenacity is also called *tensile strength.*

Example. — A test rod of aluminum bronze, 8.2 mm. in diameter, broke when stretched by a force equal to the weight of 4433.5 kg. What was its tensile strength?

$$\textit{Ans.}\ \frac{4433.5}{.7854 \times 8.2^2} = \text{the weight of 83.9 kg. per sq. mm.}$$

Experiment 28. — *Object.* To find the breaking stress and the tensile strength of a given wire or thread.

Remember that kinks and sharp bends weaken a wire or thread and must not be permitted in this work. Remember also that a jerk will break a wire which a steady stress of equal strength will not. Sudden pulls must be avoided (§ 4, *c*, *d*).

Apparatus. *A* and *B* (Fig. 46)[1] are blocks about $4 \times 2\frac{1}{2} \times \frac{7}{8}$ inches each; *p* and *p′* are posts about 1 inch in diameter, fixed upright by

[1] From Hall and Bergen, modified.

screws; *s* and *s'* are screw hooks set in a line which touches the circumference of the posts. *C* is a clamp by which one block is firmly held upon the table. *D* is a spring balance to record the stress applied. Wires No. 30, of brass, iron, steel, or copper may be used.

Operations. Clamp *A* to the table. Wind one end of the wire two or three times around the post *p*, and fasten it to the hook *s*. In like manner, make two or three turns around the other post, and fasten the end of the wire to hook *s'*. The length of wire between the posts is not important.

1. To find the *breaking stress.* Hold the spring balance in the left hand, with its hook fixed by the screw hook *s'*, *horizontally,* and on its back, and grasp its ring with the right hand. Place the eye directly over the scale, pull gently to just straighten the wire, and record the scale reading. This must be subtracted from all future readings. Why?

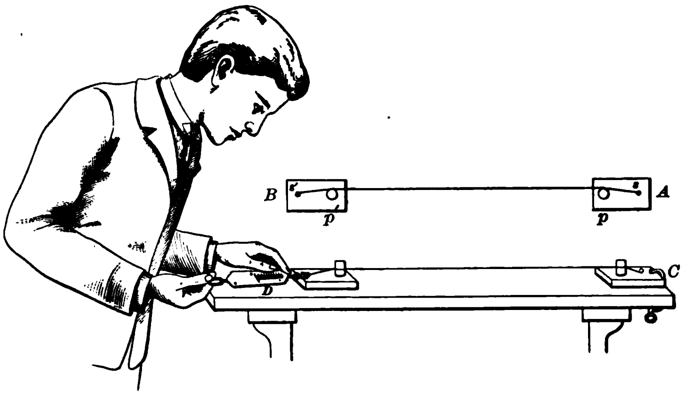

Fig. 46.

Now pull steadily, gradually increasing the stress. Keep the eye constantly above the index of the balance, and watch intently until the wire breaks. The scale reading at that moment shows the breaking stress of the wire. Repeat the experiment several times, and take the average of the results.

2. To find the *tensile strength* of the wire (§ 46, *d*). Find the diameter of the wire. This is done by using a wire gauge which gives the *gauge number*, and then taking the corresponding diameter from a table. Compute the area of a cross section ($d^2 \times .7854$). Finally compute the tensile strength, or tenacity, as in *d*.

Compare the strengths of thread, — linen, cotton, silk, — of different trade marks and different sizes, by part 1 of the foregoing experiment.

IV. MOLECULAR AND MASS ATTRACTIONS.

MOLECULAR ATTRACTION.

47. **Cohesion.** — *a.* If a solid body is built up of molecules (§ 34), there must be a mutual attraction which binds them together. This molecular attraction is called *cohesion.* Tenacity is due to cohesion. It is the attraction of its molecules for each other, or its cohesion, that keeps a wire from being broken by a pull, and the breaking stress (§ 46, *b*) is a measure of cohesion. Other properties of matter which you can recall could not exist but for cohesion.

Experiment 29. — *Object.* To test for the cohesion of water at its surface.

A plate of metal or glass, say 5 cm. square, is thoroughly cleaned by washing it first with a solution of caustic potash and then with water. It is suspended (*P*, Fig. 47) by four fine threads cemented to its surface, one at each corner, below the pan of a specific gravity balance, so as to lie in a horizontal position, and then carefully balanced by sand or shot in the opposite pan.

Place a vessel of water below the plate, and adjust it until the plate lies on the water when the balance beam is horizontal, excluding all air bubbles by letting one edge of the plate touch the water first, and then slowly lowering the other edge. Proceed to put small box-masses on the pan until the plate is lifted. Note the sum of the masses used.

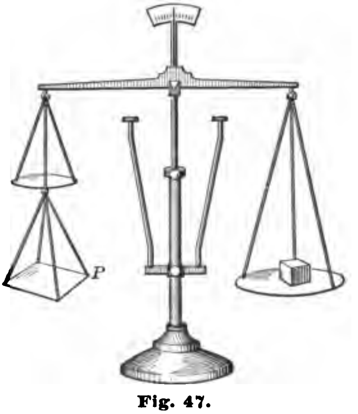

Fig. 47.

Examine the under surface of the plate, and you will find it covered with a film of water. Instead of pulling the plate from the water, the

masses have evidently pulled a film of water off the surface of the water in the vessel. This makes it clear that there is an attraction which holds the molecules of water together. The breaking stress of the water is the weight of the masses which pulled the film off, and to compute the cohesion of the water per sq. cm. which was overcome by this weight, proceed as in § 46, *d*. We have:

$$\text{Cohesion per sq. cm.} = \frac{\text{weight of the masses}}{\text{area of the plate}}.$$

Make the computation and state the results in milligrams per sq. cm.

b. The fact that a film of water was carried off by the plate in the foregoing experiment shows that there is an attraction between the metal and the water. Such mutual attraction of molecules of different kinds of matter is often called *adhesion*. The molecules in a crayon are held together by cohesion, but they are held upon a blackboard by adhesion.

c. There is a slight cohesion in liquids; it is stronger in some liquids than in others. There is adhesion between liquids and solids. A hand, when withdrawn from water, is wet; why should it be so? Let the hand be withdrawn from a bath in mercury, and it emerges without a drop of that liquid clinging to it. The fact is that while the adhesion between the hand and water is stronger than the cohesion in the water, the adhesion between the hand and mercury is weaker than the cohesion in mercury. Why do the feathers of a bird shed water so well?

d. A broken solid, such as a fractured vase, cannot be mended by pressing the pieces together, however nicely they may be fitted to their places. This fact suggests that the attraction of molecules can extend only through a distance insensibly small. This distance has been estimated to be .000005 cm. The edges of the pieces of the vase cannot be pressed close enough together to bring their molecules within the range of their mutual attractions.

Possibly the vase may be mended by using a cement. The cement between the pieces unites them by its adhesion to both

edges between which it is placed. But for this purpose it must be applied as a liquid or a very soft solid, so that it will flow, or may be pressed, into such close contact with the edges that the molecules shall be within the range of their mutual attraction. It must then be allowed to harden by cooling or drying until its own cohesion is strong.

e. Plastic solids, like wax and red-hot iron, may be made to cohere by pressure. Two pieces thus become a single mass. This explains the process of welding. When the ends of two iron bars are heated to redness, laid one upon the other, and pounded with hammers, or pressed between heavy rollers, they cohere. The two bars become one, which is, when cold, as strong at the junction as elsewhere, simply because the molecules of the two pieces have been driven within the minute range of their mutual attractions.

48. **Surface Tension.** — *a.* A dry sewing needle, if laid carefully on the surface of water, will float. Try it. The same needle, if put never so little below the surface, will sink. Examine the needle as it rests on the water, and you will see that it lies in a trough much larger than itself. The surface film of the water is really bent, but not broken, by the weight of the needle. This is one of many facts which show that the surface film of water acts as if it were a thin skin, very elastic, somewhat tough, and tightly stretched over the water. An elastic membrane stretched over the water would support a mass in much the same way.

The free surfaces of other liquids behave in a similar manner. The stress which exists in the surface film of a liquid is called *surface tension.*

Experiment 30. — *Object.* To measure the surface tension of water, and compare the surface tension and viscosity of water and soap solution.

1. Make a rectangular fork (Fig. 48, *f*) by bending a wire, about 15 cm. long, making the legs about 6 cm. each and the crosspiece about 3 cm. Suspend the fork from the hook of a balance by means of a fine thread tied to the middle of the crosspiece, and place the legs in a vessel

of pure water. Counterpoise the fork with sand, and adjust the water so that the crosspiece shall be about 1 cm. above its surface when the beam is horizontal. Depress the beam until the crosspiece is under water. Notice that the water holds it down. Then add small masses, gently, to the counterpoise; a film of water will be lifted in the rectangle of the fork, and the masses may be carefully increased until their weight is just able to break the stretched film. The experiment should be repeated, and the greatest stretching weight which the film bears should be noted each time. These values should not differ very much, and the average may be taken as the breaking stress of the film.

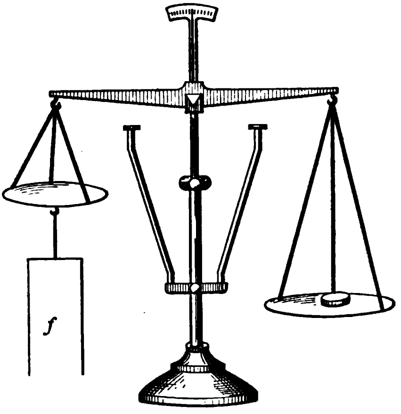

Fig. 48.

But the film has two surfaces, and its tension must therefore be double the tension of a single-surface film, like that of the free surface of the water in the vessel. Moreover, the film is about 3 cm., or the length of the crosspiece, wide.

Hence to compute the surface tension per cm. width, we have,

$$\text{Surface tension} = \frac{\text{breaking stress}}{2 \times \text{width of film}}.$$

In an experiment with water (not pure) at 18° C., the following result was obtained:

Width of film, or length of the crosspiece $= 2.6$ cm.

Breaking stress $=$ the weight of 390 mg.

$\therefore$ Surface tension per cm. $= \dfrac{390}{2 \times 2.6} =$ the weight of 75 mg.

The true value for pure water at 20° C. is the weight of 75.7 mg. per cm. Small quantities of impurities reduce the surface tension considerably, and this may account for the smaller value obtained.

2. Find the surface tension of soap solution by the method just described. Notice whether the soap solution or water has the larger and tougher film. Which has the greater surface tension?

b. By comparing the results of experiments made with water and soap solution, we discover that the extent to which a film

may be stretched is not determined by the surface tension of the liquid. It is due to another property, which is called *surface viscosity.*

A soap film may be enormously stretched, as when a large soap bubble is blown, because the surface viscosity of the solution is great. A bubble cannot be blown with water because the surface viscosity of water is small. Yet the surface tension of water is much greater than that of soap solution.

The froth which is easily produced on some liquids consists of a multitude of minute bubbles. Froth cannot be raised on pure water because its surface viscosity is so small.

Experiment 31. — The tension of soap solution may be exhibited as follows (Appendix IV., 1):

Blow a soap bubble four or five inches in diameter, and remove the lips from the pipe (Fig. 49, 1). The bubble will at once begin to shrink, and continue to do so with increasing rapidity until it finally shrivels into the pipe bowl (Fig. 49, 2). On account of its surface tension the film contracts upon the air within and expels it from the outlet.

In like manner the surface film of a drop of water contracts upon the water within. There is no outlet for the water inclosed, and its reaction (§ 9, *g*) balances the surface tension.

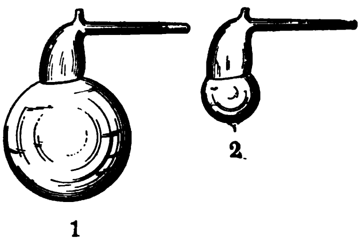

Fig. 49.

c. If a sheet of thin rubber is very tightly stretched, with its edges fastened over a hoop, and then pierced by a knitting needle, the hole will instantly be much enlarged (Fig. 50), because the stretched sheet will spring back in all directions toward the hoop. Now if you will properly break the surface film of water, that too may be seen to spring in all directions away from the puncture.

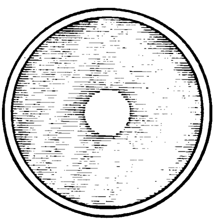

Fig. 50.

Fig. 51 represents a dish containing water. With the point

of a pen place a little ink on the center of the water surface. The ink breaks the surface film, which instantly springs away and carries the ink with it to a considerable distance. It springs away for the same reason that a stretched rubber sheet or cord springs back when released, because its molecules attract one another.

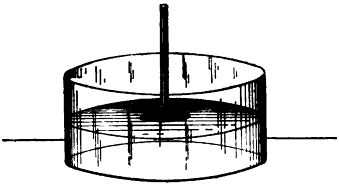

Fig. 51.

d. But why is this action confined to the surface? Because the molecules everywhere below the surface are attracted by one another equally in all directions, while those at the surface are attracted by others only downward and sidewise. There is no attraction upward on the surface molecules but that of the molecules of the air above, and the downward and sidewise pulls of the water molecules below are much stronger than that.

In regard to the probable thickness of the surface film, to which all the phenomena of surface tension are due, consult § 47, *d.*

49. **Some Effects of Surface Tension.** — *a.* If a piece of glass be inserted in water, the surface film will be cut, but instead of springing away (§ 48, *c*) it will rise a little distance alongside the glass (Fig. 52). It rises because the attraction between molecules of glass and those of water is stronger than that between molecules of water (§ 47, *c*).

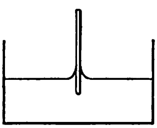

Fig. 52.

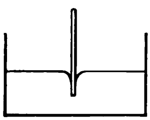

Fig. 53.

If a piece of glass be inserted in mercury, the surface film of mercury will be cut and the liquid will sink below the level (Fig. 53). It sinks because the attraction between the molecules of glass and those of mercury is weaker than that between molecules of mercury.

Examine the surface of water in a small goblet; is it as high in the center as it is around the edges? Explain.

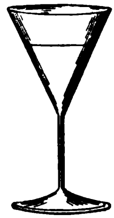

Fig. 54.

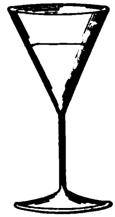

Fig. 55.

Examine the surface of mercury in a small goblet; is it as high in the center as it is around the edges? Explain.

b. The mutual action of solids and liquids, by which the surface of the latter is raised or lowered, is commonly called *capillarity*. It receives this name because solids in the form of small tubes (*capillus*, a hair, hence hairlike tubes) show it in the highest degree. *T* (Fig. 56) represents a small open glass tube inserted in water. *h* represents the top of the column of water which was instantly lifted within. Try it.

T (Fig. 57) represents a small glass tube inserted in mercury. *h* represents the top of the mercury within. Try it. Notice the different shapes of the surface within the tubes; the surface of water is concave; that of the mercury, convex.

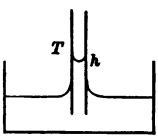

Fig. 56.

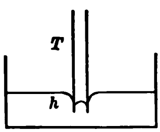

Fig. 57.

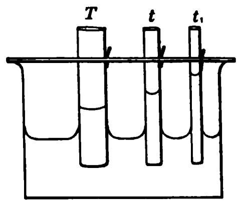

Fig. 58.

c. *T*, *t*, t_1 (Fig. 58), represent tubes of different diameters, supported on the top of a beaker by a bar of wood with holes a little larger than the tubes, in which the tubes are kept from slipping by little wedges of wood. Each tube was lowered nearly to the bottom of the beaker, so that the water would rise and wet the glass inside. It was then lifted and fastened by the wedge. The water fell down in the tubes to the levels shown. Try it. (Appendix IV., 2.)

This experiment reveals the fact that a liquid is lifted to greater heights in tubes of smaller diameters. But the precise relation between the heights and the diameters,—in other words, the law which governs the rise of a liquid in capillary tubes, can be discovered only by careful measurements, under fixed conditions. The following facts and laws have been revealed:

1. If very clean water is used, with the cleanest possible glass tube and vessel, it is found that, at a temperature of 18° C., water will rise in a tube 1 mm. in diameter to a height of 29.79 mm. (almost 3 cm.).

2. In tubes of different diameters at the same temperature, the elevation of a liquid which wets the tubes, or the depression of one which does not, varies inversely as the diameters.

3. The elevation or depression varies with temperature; it becomes less as the temperature rises. An elevation at 100° C. will be about four fifths of what it would be at 0° C.

4. The elevation in wetted tubes is almost independent of the material of the tube.

5. But depression in tubes not wetted is different in tubes of different materials.

6. Both elevation and depression are independent of the thickness of the tube.

7. But both elevation and depression depend on the nature of the liquid.

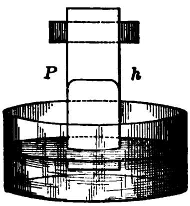

Fig. 59.

d. Capillary action is prettily shown by glass plates (Fig. 59).

P represents two strips of window glass about 5 inches long and $1\frac{1}{2}$ inches wide, side by side, separated by a strip of thin cardboard at the top. *h* represents the surface of water which instantly rises between these parallel plates when they are inserted in that liquid. Try it. Explain the fact that the surface at *h* is lower at the edges of the plates.

P (Fig. 60) represents two strips of window glass, making a small angle with each other, and inserted in water. *h* represents the surface of the

water which rises between the plates. Try it. In order to succeed best, clean the glass by immersing it in caustic soda and then rinsing it in pure water. Explain the fact that the water rises to different heights at different places between the plates.

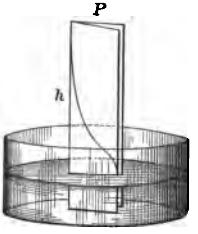

Fig. 60.

e. Capillary action is shown by all bodies in which interstices exist. Thus the rise of oil in a lamp wick, the absorption of water from below by loose soil, the spreading of water through cloth, and its absorption by sponge and by wood, are due to capillarity. In all cases the interstices, not the fibers, are the capillary tubes.

50. **Crystallization.** — *a.* Many minerals are found in nature in small masses, having definite shapes, called *crystals.* Specimens of galena, which is the most common ore of lead, are found in the form of perfect cubes, or rectangular blocks which are built up of cubes (Fig. 61). Water solidified, as frost on the window, or in snowflakes, presents a variety of definite and beautiful forms.

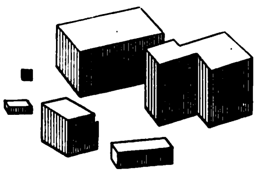

Fig. 61.

Experiment 32. — The production of crystals may be studied as follows:

1. Sprinkle powdered alum into hot water, say 20 g. of alum to 100 cc. of water, stirring the liquid until the solid is dissolved. In this solution the molecules of the alum are separated and scattered throughout the liquid. But now let it stand undisturbed for several hours. After the lapse of sufficient time, beautiful transparent bodies, of regular form, will be found in the dish.

2. In most cases crystals form at once when a hot saturated solution is allowed to become cold. Try potassium sulphate. Dissolve 25 g. in 100 cc. of boiling water, and look at the solution from time to time while it cools.

3. Crystals form slowly when a strong solution evaporates on exposure to air. The slower the evaporation, the larger and more perfect will the crystals be. Try copper sulphate. Dissolve 42 g. in 100 cc. of water, warming it gently to hasten the solution, and then let it stand *undisturbed.* In due time the crystals will form.

it. Gravity and gravitation are obedient to the same law (§ 51, *d*). But we need not take the earth's mass into account when we compare the gravities of two bodies. The earth and a cannon ball attract each other; so do the earth and a bird shot, but with much less force. The two forces are to each other as the masses of the cannon ball and the bird shot. Their *ratio* is not affected by the mass of the earth, because that is the same for both.

b. Hence the mutual attraction of the earth and the different bodies above its surface varies directly as the masses of those bodies.

Of course (§ 51, *d, e*) gravity varies also with the square of the distance from the center of the earth. But, in any one locality, there is very little difference in the distances of bodies from the earth's center. A body at the surface is, say, 4000 miles from the center; 500 feet above the surface is less than $\frac{1}{40000}$ of that distance farther away. Now if you will compare the square of 4000 and the square of $4000 + \frac{1}{40000}$, you will be able to say to what extent distance above the earth in a given locality affects the gravity of a body. Do this.

c. But owing to the *shape* of the earth, bodies on its surface, even when at the common level of the sea, are nearer the center of the earth as the locality is farther from the equator. This difference must be taken into account in measuring gravity in different latitudes.

d. Since the *weight* of a body is the measure of the earth's attraction for it, *the weights of bodies, at the same place, vary directly as their masses.* On this principle the beam balance enables us to compare the quantities of matter in two bodies (§ 4, *f*). But we are not to lose sight of the fact that a *pound* is a quantity of *matter,* while the *weight of a pound* is a quantity of *force.* Clear thinking and accurate speaking should compel us to speak of quantities of matter in terms of mass, and of gravity in terms of weight.

e. Weight should be measured in units of force (§ 13, *c*). As already stated the weight of a pound, in the latitude of New York, is 32.16 poundals, because gravity increases the speed of a falling body at the rate of 32.16 feet per second, and for a similar reason the weight of a gram is 980 dynes. Hence the weight, W, of any mass, m, if we let g stand for the acceleration, 32.16 feet per second, or 980 centimeters per second, is

$$W = m \times g.$$

53. **Studies.** — 1. How many dynes are there in one poundal? What is the weight of 20 pounds in the latitude of New York? What is the weight in poundals of 10 kilograms?

2. Is the weight of 10 pounds of flour greater or less in London than in New York? Why? By what instrument can the difference be detected? Why can we not detect the difference by a beam balance?

3. Should 50 kilograms weigh more or less on a mountain at the height of 4 miles than at the sea level? According to what law? Assume the radius of the earth (from the center to the sea level) to be 4000 miles, and find the difference in the weight of the 50 kilograms at sea level and on a mountain at a vertical height of 4 miles.

4. What velocity would a force of 35 poundals produce in a 3-pound ball in 2 minutes?

5. A 20-gram ball started from rest, and in 15 minutes it was going with a speed of 75 cm. per second; how much force was being constantly exerted to move it?

54. **Direction and Constancy of Gravity.** — *a.* Gravity is everywhere directed toward the center of the earth. This is shown by the fact that bodies everywhere, if not hindered, fall in straight lines toward that point (§ 11, *a*). These "lines of direction" seem to be parallel. Thus if balls be dropped from two adjacent windows, they will strike the ground at points which, by ordinary measurement, are just as far apart as the points from which they started. But if they start from points widely separated, this is not so. Falling bodies are directed *downward* in every country; but downward is, everywhere, toward the center of the earth.

b. Gravity is a *constant* force; it never for an instant ceases; and on the same mass, at the same place, it never varies in strength. Hence gravity not only starts a falling body, but it should impart approximately the same acceleration to it in every second of its fall. We say approximately, because as a body approaches the earth, gravity does really strengthen (§ 52, *b*), and to that extent it increases the acceleration.

c. Motion in which the velocity changes just as much in each succeeding second as in the first is called *uniformly accelerated motion*. The motion of a falling body is the best illustration. It would be a perfect example if it were not for the slight increase of acceleration due to the lessening distance from the earth, and the diminution due to the resistance of the air, which becomes very great when the motion is swift.

d. The acceleration due to gravity is the same for all masses. This was proved by Galileo. His experiment consisted in dropping unequal balls of iron from the top of the leaning tower at Pisa. He found that, whatever their masses, the balls reached the ground at the same instant. Using balls of iron and of wax, he found that those of wax lagged behind. But this could be attributed to the resistance of the air, which retarded the lighter wax balls more than the balls of iron. Thus if you will drop, at the same instant, a penny and a disk of paper, of equal diameters, the penny will hasten in a straight line, while the paper more leisurely flutters to the floor. Try it. The fact is that the resistance of the air is proportional to the area of the under surface of the falling body, while the energy of the body to overcome it is proportional to the mass of the body. Hence denser bodies are less retarded.

55. **Acceleration found by Atwood's Machine.** — *a.* Atwood's machine is an instrument by which to reduce the speed of a falling body by increasing the mass without increasing the gravity. It is necessary to do this in order to make the acceleration small enough to be measured.

The machine consists essentially of: (1) a *grooved wheel*, *D* (Fig. 64), with a long, slender, but strong silk cord passing over it, and carrying two *equal masses*, *A* and *B*, at its ends; (2) a *pillar*, *C*, six or seven feet high, supporting *D*, and graduated in inches or centimeters, with the zero at the top; (3) a seconds pendulum, *F*; (4) a *rider*, which, placed on *A*, will cause motion; and (5) a ring and platform to arrest the rider and the masses at any desired points on *C*.

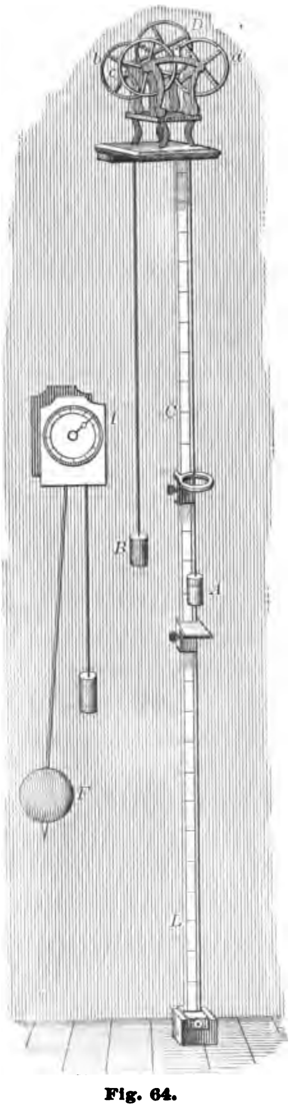
Fig. 64.

The masses *A* and *B* balance each other, and leave the rider to produce whatever motion occurs in all three together. Thus: If *A* and *B* are each 49.5 g. and the rider 1 g., there will be a total mass of 100 g. to be moved by the earth's pull on 1 g. Hence the acceleration will be only .01 as great as if the rider were falling freely (§ 11, *a*). In this way we can obtain acceleration *due to gravity*, but as small as we desire. The scale on *C* enables us to measure distance, and the pendulum, to measure time.

Set the pendulum vibrating. Place the rider upon *A*, and carry it up to the zero of the scale *C*. Find by trial where the ring must be fixed in order to arrest the rider at the end of one second. The mass *A* will be no longer moved by gravity, but will go on from the ring *with a uniform velocity, which was acquired in that first second.*

To measure it, find by trial where the platform must be fixed to arrest the mass *A* at the end of one second after it leaves the ring. The distance between ring and platform is the distance per second which the mass goes with the velocity which gravity gave it in the first second. Thus if the ring is found to be at 5 cm., the platform should be found at 15 cm., so

that the velocity *produced* by gravity in the *first second* is 10 cm. per second.

Further experiments show that 10 cm. per second is produced in each succeeding second also. It is the acceleration of the total mass, but it is produced by the weight of the rider alone. If the mass of the rider is .01 of the total mass, as we have supposed, its weight can produce only .01 of the acceleration it would produce in the rider alone. Hence the acceleration of the rider falling freely would be 1000 cm. per second.

b. Another instrument for determining the acceleration due to gravity is the pendulum (§ 69, *e*), and the accepted values have been found by its use. The best determinations show that the acceleration of a freely falling body, in the latitude of New York, is approximately 980.19 cm. per second, or 32.16 feet per second. The acceleration due to gravity is represented by g. The values just stated are the values of g at New York.

c. The acceleration of a body going vertically upward is the same *in numerical value* as that of a body falling. It differs simply in direction. Gravity retards the motion of a body upward and hastens its return, but the *change of velocity per second* is the same in value. When the velocity *increases*, the acceleration is said to be *positive*, and when it *diminishes*, the acceleration is said to be *negative*.

56. **The Laws of Falling Bodies.** — *a.* By the "laws of falling bodies" we mean general statements of the relations which exist among the values of time, distance, speed, and acceleration in a motion due to gravity. These laws may be ascertained by experiments, or they may be derived as inferences from facts already known. Let us take the latter method.

b. Since the acceleration of a body is the velocity acquired in one second, the total velocity at the end of any number of seconds must be equal to acceleration × time. Or writing the symbols of these three quantities instead of words:

$$v = gt. \tag{1}$$

But g, *at any given place*, is the same for all bodies, so that, at that place, the value of v depends on t only. Hence we

may translate the equation as follows: *The final speed of a falling body at any given place varies directly as the time occupied in its fall.* This is the first law of falling bodies.

But g is not the same everywhere, and hence we translate the equation for different places with reference to g, by supposing the time, t, to be the same for bodies at the two places where g differs. It will then read as follows: *The final speed of a falling body, acquired in equal times at different places, varies directly as the force of gravity.* This is the second law.

c. But the equation not only shows what the laws are; it also shows how to solve problems. By substituting the known values of either two of the quantities involved, that of the third may be found.

Example. — If an apple reaches the ground with a speed of 10 m. per second, how long was it in falling from the branch? $v = gt$ becomes $1000 = 980 \times t$. *Ans.* 1.02 seconds.

d. Next let us start with the fact that the distance traversed in one second is numerically equal to the average speed during that second (§ 10, *d*). This is true for any other length of time. For example: If a body starts from rest, and at the end of 5 seconds has a speed of 80 cm. per second, its *average* speed (during the 5 seconds) is $0 + 80 \div 2$, or 40 cm. per second. The *total distance* is just the same whether the body starts with zero speed and ends with 80 cm. per second, or goes at the uniform speed of 40 cm. per second from the start, so that in the 5 seconds the whole distance must have been 40×5, or 200, cm.

But we have just seen (*b*) that the final speed of a falling body at the end of t seconds is gt. Its average speed, if it start from rest, is $\frac{0 + gt}{2}$, or $\frac{1}{2}gt$, and this multiplied by the number of seconds, t, gives the total distance, $\frac{1}{2}gt^2$. Let s[1] stand for total distance traversed, and we have

$$s = \tfrac{1}{2}gt^2. \qquad (2)$$

[1] s is set apart in physics to denote distance traversed, as g is set apart to denote acceleration by gravity, and t to denote time.

We may translate Equation (2) as follows: *The distance through which a body falls in a given time at any one place varies as the square of the time.* This is the third law.

To solve problems by Equation (2), substitute known values for any two of the three letters.

Example. — An arrow which was shot vertically upward, returned to earth in 6 seconds after leaving the bow; to what height did it rise? The arrow would take just as long to go up as to return; hence it was 3 seconds in falling. Then if g is 32.16, $s = \frac{1}{2} gt^2$ becomes $s = \frac{1}{2} \times 32.16 \times 9$.

Ans. 144.7 feet, approximately.[1]

e. Now that we have the two equations (1) and (2), let us see what we shall get by combining them algebraically. Thus:

From (1) we find that $t = \dfrac{v}{g}$ and $t^2 = \dfrac{v^2}{g^2}$.

From (2) we find that $t^2 = \dfrac{2s}{g}$.

Equating these values of t^2, we have $\dfrac{v^2}{g^2} = \dfrac{2s}{g}$.

Hence, $$s = \frac{v^2}{2g}, \tag{3}$$

and also $$v = \sqrt{2gs}. \tag{4}$$

We may translate Equation (3) as follows: *The distances traversed by bodies falling freely at a given place vary directly as the squares of their final speeds.* This is the fourth law.

We may translate Equation (4) as follows: *The final speeds of falling bodies, at a given place, vary directly as the square root of the distance through which they have fallen.* This is the fifth law.

57. **Gravity, the Type of a Class of Forces.** — All forces which are, like gravity, *continuous* and of *uniform strength,* will produce uniformly accelerated motion. The value of acceleration will, of course, depend on the value of the force; but in any

[1] We have neglected the fact that the arrow starts *from the bow,* while it falls *to the earth;* it must be a trifle longer coming down than going up.

case it may take the place of g, and then the formulas for falling bodies will apply to all uniformly accelerated motions. The letter a is set apart in physics to represent acceleration in general. Put a in place of g. Then (Equation 1),

$$v = gt \text{ becomes } v = at.$$

In like manner you should transform each of the other three equations.

58. **Studies.** — 1. A marble, dropped from a window in a house in New York, was observed to strike the sidewalk in 2 seconds; how high was the window above the walk?

2. From a balloon at a height of 1000 feet, a bag of sand was dropped; how long a time did it take to reach the earth? (Take $g = 32.16$ feet.)

3. A stream of water is to be thrown to the roof of a building which is 80 feet above the nozzle of the hose of the fire engine; with what velocity must the water leave the nozzle?

4. With what average velocity would you need to walk in order to go a half mile in six minutes (§ 10, *e*)?

5. A ball rolling down a long inclined plane reached its foot in 10 seconds, and had acquired a speed of 4 feet per second; what was its acceleration? What was the length of the plane? How far did it go in the first second from the start?

6. A train with the brakes on passes the door of a station with a velocity of 95 feet per second, and an acceleration of -4 feet per second; how long before it stops?

7. If the steam which drives a train is kept up with uniform pressure, why does not the motion of the train continue to be uniformly accelerated, instead of soon becoming approximately uniform? When the motion of the train has become uniform, while the full power of steam is still on, what work is the engine doing?

8. How does the atmosphere affect the motion of a falling body? Explain.

9. If a hailstone weighing $\frac{1}{2}$ an ounce falls from the height of a mile, with what *energy* would it strike the earth if there were no atmosphere to retard it?

10. A ball thrown vertically downward from a tower 100 feet high, leaves the hand with a velocity of 12 feet per second. With what velocity would it strike the earth if the air did not retard it?

Summary of Units.

59. **The Two Systems.** — *a.* A quantity is *measured* by finding how many times a definite quantity of the same kind, called a *unit*, is contained in it. A quantity is *expressed* by stating the *name* of its unit with the *number* prefixed; *e.g.* 1 foot, 10 seconds, 4 pounds.

b. There are two *systems* of units, the *English* and the *Metric.* The first is used chiefly in the United States and England; the second is international.

c. There are only three *fundamental units.* They are the units of *length, mass,* and *time.*

The English . .	yard . .	pound . .	second;
The Metric . .	meter . .	kilogram .	second.

All other units are derived from these, and hence are called *derived units.*

d. In the measurement of all quantities for scientific purposes, the units are *derived* from the metric fundamentals. They are the centimeter, the gram, and the second. The system founded on these fundamental units is called the "centimeter-gram-second system," or, briefly, the C. G. S. system.

60. **Derived Units.** — The following is a list of some derived units in the English and the C. G. S. systems, which have already been defined in connection with our study of the various quantities:

Quantities.		*English.*	*C. G. S.*
Area	(§ 2, *a*, *f*),	square inch . . .	square centimeter.
Volume	(§ 3, B, *a*),	cubic inch	cubic centimeter.
Velocity (speed)	(§ 10, *c*),	1 ft. per sec. . . .	1 cm. per sec.
Acceleration	(§ 12, *b*),	1 ft. per sec. each sec.	1 cm. per sec. each sec.
Force	(§ 12, *c*),	poundal	dyne.
Weight, Absolute	(§ 13, *c*),	poundal	dyne.
Work, Absolute	(§ 15, *b*),	foot-poundal . . .	erg.
Energy, Absolute	(§ 17, *f*),	foot-poundal . . .	erg.
Activity	(§ 16, *b*, *c*),	550 foot-pounds per sec.,	watt.

V. SIMULTANEOUS FORCES AND MOTIONS.

COMPOSITION OF FORCES AND MOTIONS.

61. **Simultaneous Forces.** — Newton's First Law of Motion (§ 4, *c*) declares that a body once started will move forever *if left to itself.* But Nature never leaves a body to itself. The mutual actions and reactions of all bodies are unceasing, and every body is subject to several forces at the same time. Two or more forces acting upon a body at the same time are called *simultaneous forces.*

In this section we are to see how two or more forces, acting at the same time, combine with each other in producing effects.

62. **Composition of Forces.** — *a.* Two simultaneous forces will combine to produce one motion. This fact may be illustrated as follows:

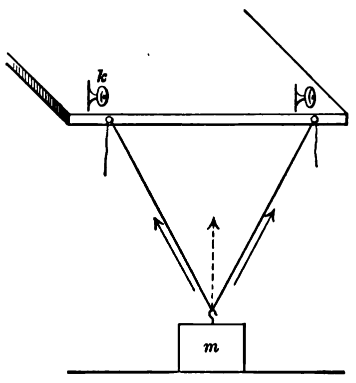

Fig. 65.

Experiment 33. — Fix the middle of a cord to a block of iron or other mass (m, Fig. 65), resting on the floor, and pass the ends over smooth knobs (k) screwed into the edge of the table.

Then pull both ends, *equally,* and the mass will go toward neither knob, but vertically upward. If you pull more strongly with the right hand than the left, the mass will take some path to the right of the vertical. The direction of the mass is always a compromise between the directions of the two pulls.

It is evident that the two oblique forces lift m exactly as one force would do if it were to pull with the right strength and in the direction

which *m* actually takes. So in every case, where there are two forces upon the same point at once, there is always some one force which, alone, would produce the same effect.

b. Three things are to be mentioned in order to *describe* a force: First, its *magnitude*, by which we mean its value in dynes, or poundals, or other units of force; second, its *direction;* third, its *point of application*, by which we mean that point in the body at which it is applied.

c. A force may be *represented* to the eye by a line. The length of a line represents the magnitude of a force. *The end of the line represents the point of application.* An arrowhead on the line, pointing away from the point of application, or toward it, represents the direction. Thus a line *ab* (Fig. 66), which is 30 mm. long, may represent a force of 30 dynes, applied to a bar at *a* and pulling toward *b*. Likewise *ca*, 20 mm. long, represents a force pushing to the left, on the bar at *a*, and equal to 20 dynes. The point of application is *a*.

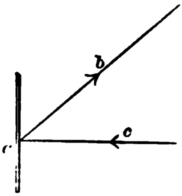

Fig. 66.

Experiment 34. — *Object.* To find a single force which, alone, will have the same effect as two given forces acting together at the same point but in different directions.

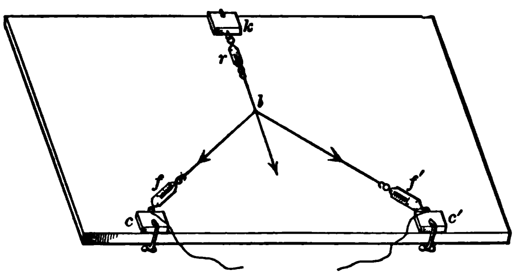

Fig. 67.

Fig. 67 represents the apparatus. Two forces are to be applied to a loop in a cord at *l*, by means of two spring balances, *f* and *f′*, pulling in the directions of the arrows. A third balance, *r*, is fixed to a block, *k*,

which is clamped to the table. Very flexible, strong cord should be used. A piece of convenient length is made double by tying its ends together, and then fixed on the hook of *r*. A longer cord is passed through the loop and then fixed upon the hooks of *f* and *f'*. Blocks, *c* and *c'*, are clamped on the front edge of the table, and cords from the rings of *f* and *f'*, passed through their hooks, will enable one person to pull both balances at once. It is better that a second person should read the scales.

The balances should lie flat on their backs.

Their hooks should be supported in a horizontal position to avoid friction of the index.

The scales should be read with the eye directly over the index. Why?

Operations. Pull the cords of *f* and *f'*, and fasten them. Jar the balances to relieve the index from friction. Record the readings of the three scales in the tabular form. Readings *f* and *f'* measure the two forces applied to *l*, and *r* measures their combined effect on *l*.

Scale *f*	Scale *f'*	Scale *r*

Next proceed to represent these forces. Thus: Place your open notebook under the cords, and make pencil dots on the page, one, *o*, directly under the loop *l*, and others *a*, *b*, *c*, between *l* and each balance, placing them carefully under the cords. Remove the book.

Draw lines from *o* through *a*, *b*, and *c*, to show the *directions* of the forces (Fig. 68). Lay off from *o* on the lines *oa* and *ob* as many inches or centimeters as there are units of force in *f* and *f'*. These lines, *of* and *of'*, represent the two forces.

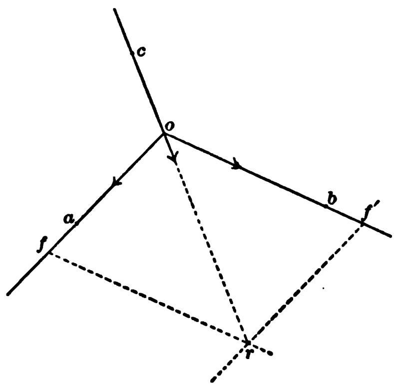

Fig. 68.

From *f* and *f'* draw dotted lines, parallel respectively to *of'* and *of*, to complete a parallelogram, and draw the diagonal *or*. If the work has been very well done, the diagonal will be the line *co* prolonged; and on measuring it, the length contains as many units as there are units of

force in *r*. So that a single force, *or*, would have the same effect on a body at *o*, as the two forces *of* and *of'*. The experiment should be repeated with different forces, which may be done by clamping block *k* at different places on the table, and perhaps also changing blocks *b* and *c*.

d. When two forces on one point can be represented by the two adjacent sides of a parallelogram, they may be replaced by one force, which is represented by the diagonal of the same parallelogram. This important principle is called the *parallelogram of forces*. The two separate forces are called *components*. The equivalent single force is called the *resultant*.

e. To find the resultant of two component forces on one point of application, but not directed in the same straight line: *First construct a parallelogram whose adjacent sides represent the two forces, and second, draw and measure the diagonal.*

Example. — Two forces, one the weight of 5 pounds, the other of 8 pounds, are applied to a body at *a* (Fig. 69), and directed as shown by the arrows at an angle of 60°; find the direction and magnitude of their resultant.

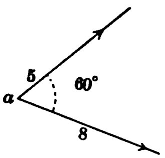

Fig. 69.

To do this, mark the point of application, *a* (Fig. 70), on your paper. Let a line $\frac{1}{4}$ of an inch long represent the weight of 1 pound. Then with a protractor draw lines *am* and *an*, making an angle of 60°, and lay off *ab*, five $\frac{1}{4}$-inches to represent the magnitude of one force, and *ac*, eight $\frac{1}{4}$-inches to represent that of the other. From *b* draw a dotted line parallel with *ac*, and from *c* another parallel with *ab*. Having thus constructed the parallelogram, draw the diagonal *aR*. This line *aR* represents the resultant of the forces, — its point of application by *a*, its direction by $a \longrightarrow R$, and its magnitude by the length *aR*, since the number of quarter inches is the number of pounds whose weight is the force.

How would you construct the resultant if the 5-pound force were in the direction *ba* instead of *ab*?

f. The single force represented by the diagonal *aR* is the *equivalent* of the two forces 5 and 8. Whatever the two together can do, this one alone can do. It can replace them without changing the effect on *a*. A train may be passing a station at the rate of 5 feet per second, and from the rear platform, when it reaches *a*, a mail pouch may be thrown toward *n*

on the station platform with a velocity of 8 feet per second. The pouch would strike the station platform at *R* in just one second, because it leaves *a* with two motions — one given by the hand, the other by the train; but if the train had been

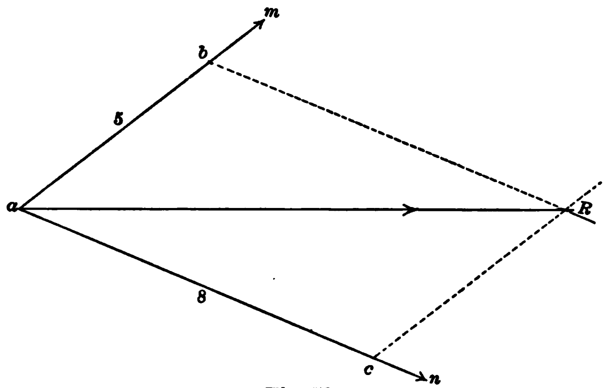

Fig. 70.

standing still at *a*, and the pouch had been thrown from *a* toward *R*, with the force represented by *aR*, it would traverse *aR* in the same time.

g. The resultant of more than two forces can be found by repeating the construction required for that of two.

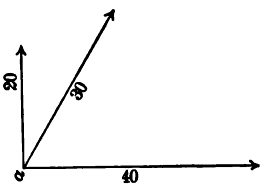

Fig. 71.

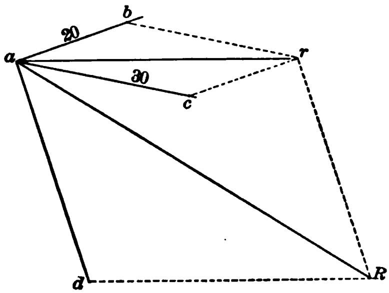

Fig. 72.

In Fig. 71 a particle at *a* is subject to three forces whose magnitudes and directions are shown. The resultant of the

20-unit and the 30-unit forces may be found; it is represented by *ar*, Fig. 72. Then the resultant of *ar* and the 40-unit force may be found; it is represented by *aR*, and is the resultant of the three given forces.

The process of finding a single force which would be equivalent to two or more actual forces on a body, is called the *composition of forces.*

63. **The Resolution of Force.** — *a.* The force represented by *aR* in Fig. 70 would be equivalent to the two actual forces *ac* and *ab;* then evidently the two forces *ac* and *ab* would be equivalent to one actual force *aR.* It is evident that one force may be replaced by two others without changing the effect on a body.

b. It is also evident that, if a single force which may replace two others is found by making a parallelogram and measuring its diagonal, then, conversely, the two forces which could replace the one, is to be found by making a parallelogram on the line that represents that one, as a diagonal, and measuring the adjacent sides.

c. To see how this may be done, let us study the following example:

A force of 32 poundals urges a body from a point, *A*, vertically upward to *B* in 20 seconds. We desire to replace this one by two others directed upward at angles of 45°; what must be their magnitudes?

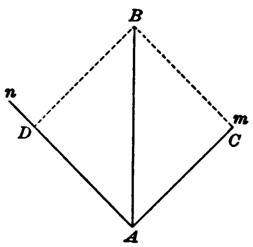

Fig. 73.

Let us represent the forces on a scale of 16 poundals to the inch. Draw a vertical line, *AB* (Fig. 73), 2 inches long to represent the 32 poundals. From *A* draw lines *Am* and *An*, each making an angle with *AB* of 45°, to represent the directions of the desired forces. Complete the parallelogram by drawing from *B* a line, *BD*, parallel with

Am, and another, *BC*, parallel with *An*; then *AC* and *AD* represent the desired forces. By measuring these lines we find the number of poundals which they represent.

d. The process of finding two or more forces which would jointly have the same effect on a body as a single force, is called the *resolution of force.*

e. The same force can be resolved into any number of pairs of components, because one line may be the diagonal of any number of parallelograms. But if the directions of the components required are given, only one parallelogram can be constructed. In that case the problem is definite and can be easily solved, as in the following case of a ball on an inclined plane.

f. Sometimes a body moves in a direction different from that of the force which urges it. But this would seem to contradict Newton's Second Law of Motion (§ 11, *a*). All such cases can be explained by the resolution of forces.

A ball on an inclined plane is a good example. Gravity is the only action on the ball *m*, on the plane *AB* (Fig. 74). But gravity is directed toward the center of the earth, while the ball rolls toward *B*. The fact is that only *a part* of its gravity is useful to urge the ball onward. This will be seen by resolving gravity into two components.

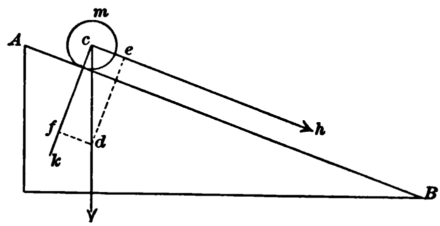

Fig. 74.

Draw a vertical line and lay off on it *cd*, to represent the full strength of gravity on the ball. Draw *ch* to represent the direction of the motion, and *ck* perpendicular to *AB*. Complete the parallelogram by drawing *de* and *df* parallel, respectively, to *cf* and *ch*. The two forces represented by *ce* and *cf* are equivalent to gravity, represented by *cd*. But *cf* is perpen-

dicular to *ce, and a force cannot cause motion in a direction at right angles to its own.* Hence the force which *cf* represents takes no part in rolling the ball down the plane; it is completely balanced by the reaction of the plane. But the force represented by *ce* is entirely free from the plane, and has nothing to do except to pull the ball along. By measuring *cd* and *ce*, we can find what fractional part of gravity does that work.

Example.—If *m* is a mass of 6 pounds, *cd* represents the weight of 6 pounds. If *ce* is found to be one half the length of *cd*, then it represents the weight of 3 pounds, and would show that only half of the actual gravity on the ball is useful in urging the ball down the plane.

64. **Parallel Forces.**—*a.* Two forces may be in parallel directions, as when a carriage is drawn by a span of horses. Such parallel forces must have different points of application. Parallel forces may urge a body in the same, or in opposite, directions. We proceed to study the first of these two cases.

b. The two men represented in Fig. 75 are supposed to have lifted the block of stone from the ground by lifting vertically on the ends of the bars. Their two forces combined raised the stone. But a single force applied directly to the stone, if strong enough, would have done the same thing. These two parallel forces are equivalent to a single force in the same direction.

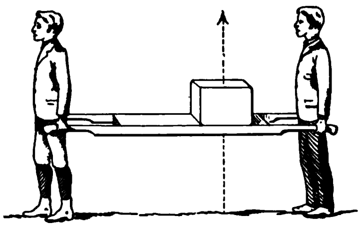

Fig. 75.

Experiment 35.—*Object.* To find the resultant of two parallel forces directed the same way.

Fig. 76 represents the apparatus. Two forces are to be applied to a meter bar, *AB*, by means of spring balances, *f* and *f'*, pulling in the directions of the arrows. A third balance, *r*, is fixed to a block, *k*, which is clamped to the table, and its hook is inserted in a loop of cord extending from the bar. Very flexible, strong cord should be used. A piece of convenient length is made double by tying its ends together, and then slipped upon the bar, and also over the hook. Other blocks could be

clamped on the front edge of the table, and cords from the rings of f and f' passing through their hooks would enable one person to pull both balances. But the better way is for two persons to work together, each managing one balance.

The bar should move over the table with the least possible friction; let it slide on polished lead pencils, or other smooth rods which raise it to

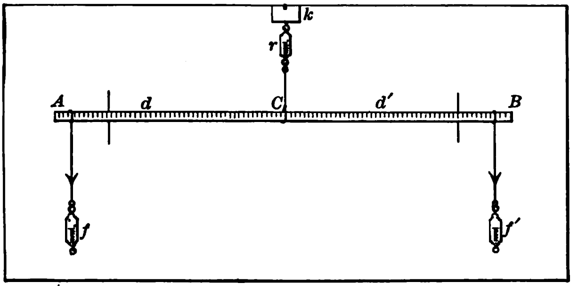

Fig. 76.

the level of the hook of r, which should also be supported in a horizontal position.

Keep the cords of the three balances always parallel, and the meter bar always perpendicular to the cords. Read the scales with care.

Operations. Pull the balances f and f', observing the above precautions. Read their scales and the scale of r. (The two former show the magnitudes of the two forces, and the latter, the magnitude of their resultant.) Read also the distances, d and d', from C to the cords on the meter bar. Record these values. Obtain another set by sliding the loop C to another place on the bar, and repeating.

Experiments.	Force f.	Force f'.	Resultant r.	Distance d.	Distance d'.	$f \times d$.	$f' \times d'$.
1							
2							
3							
4	575 g.	800 g.	1362 g.	52.3 cm.	37.7 cm.	30,172	30,160

In one experiment the set of observations of the values found are recorded above. The least count of the balances was 25 g. In this experiment observe the following points:

1. $r = f + f'$ *nearly;*
2. $f \times d = f' \times d'$ *nearly.*

See whether you find the same things true in every set of your own results. Finally, show that these results verify the statement made below in *c*. (Appendix II.)

c. The resultant of two parallel forces directed the same way is a force whose magnitude is the sum of their magnitudes, whose direction is the same as theirs, and whose point of application is between theirs, so that *it divides the whole distance into two parts which are to each other inversely as the magnitudes of the two forces.* This statement is only a translation of the results of Experiment 35. Equation (2) gives the italicized part, as explained in Appendix II.

d. Any number of parallel forces directed the same way are equivalent to one force, also directed the same way, whose magnitude is the sum of theirs. Its point of application would be found by combining the forces two by two according to the principle just stated. (Compare § 62, *g*.)

65. **Parallel Forces in Opposite Directions.** — *a.* Let a bar *AB* (Fig. 77) be pulled upward at *a* by a force of 6 units, and downward at *c* by a force of 10 units. If left to themselves, these forces would lift *A* and lower *B*. A third force of 4 units at *b*, upward, would prevent that motion; in other words, it would *balance* the forces 6 and 10. But, evidently, the 4 units could balance another single force of 4 units downward at *b*. So this single force, *R*, of 4 units downward at *b*, is equivalent to the two opposite forces 6 and 10; it is their resultant.

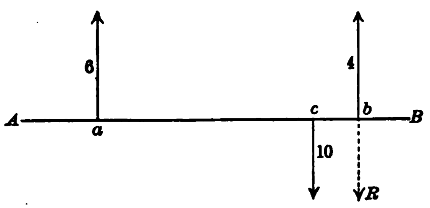

Fig. 77.

b. Now this resultant is equal to the difference of the two components, and in the direction of the greater. Its point of application is not between those of the two components, but

outside them on the side of the greater. Nevertheless it is so situated that if each force be multiplied by the distance between its point of application and that of the resultant, the two products are equal (Experiment 35 and § 64, *c*).

The resultant of any two parallel and opposite forces on any body is to be described in the same way.

c. There is, however, one peculiar case. It is that of two parallel and opposite forces *which are equal*.

Let two forces, 6 poundals and 6 poundals, at *a* and *c* (Fig. 78), pull the bar equally in opposite directions. Their resultant, equal to their difference, is nothing. No point could be found, short of infinity, on either side of *a* or *c* such that the products of *F* and *F'*, by their distances from it, should be equal. In other words, these forces have no resultant.

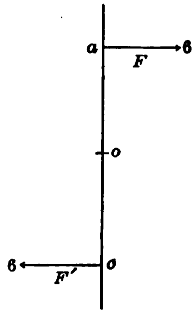

Fig. 78.

In fact, two parallel, equal, and opposite forces on a body are not equivalent to any single force whatever. They must turn the body around a point *o*, between them, unless they are balanced, and they cannot be balanced except by another pair, just equal to them, in the opposite direction on the same points *a* and *c*. Two equal parallel forces on a body in opposite directions are called a *couple*.

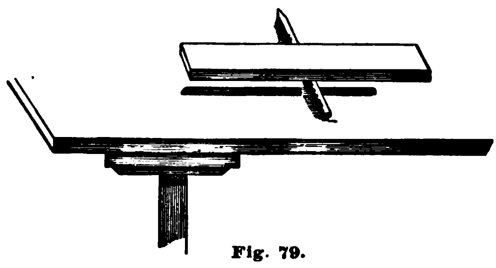
Fig. 79.

66. **Center of Gravity.** — *a*. It is quite easy to balance a body on a lead pencil lying on the table (Fig. 79). Do this,

and study the conditions of the case. Notice the facts as follows: When the body is balanced there must be just as much of its weight to the left of the pencil as to the right of it. A point exactly over the axis of the pencil and half way through the thickness of the body, and half way through its width also, must be the center of the weight of the body.

Likewise, there is a point somewhere in every body which is the center of weight; it is usually called the *center of gravity.* The same point is also the center of mass (§ 4, *a*).

b. Now the earth pulls every molecule (§ 31, *e*) of a body downward just as if it were not bound to its neighbors by cohesion (§ 47, *a*). In fact there are as many downward forces on a body as there are molecules in it. Let us imagine just a few of these downward forces on a bar to be represented in Fig. 80.

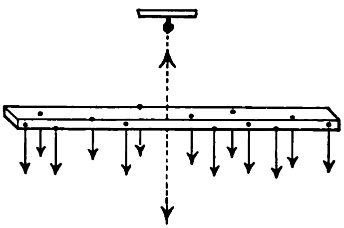

Fig. 80.

The gravity of a body is a multitude of equal parallel forces in the same direction. But all these forces are equivalent to a resultant (§ 64, *d*). In the case of the bar this resultant is equal to the sum of all the parallel forces, one to each molecule, and its point of application is the central molecule of the mass of the bar.

The point of application of the resultant of the gravity of all the molecules of a body is the *center of gravity.*

c. We may therefore, if we choose, consider the whole mass, or the whole weight, of a body as concentrated at its center of gravity. If it were actually so the body would behave exactly as it really does.

If, for example, we support the center of gravity of a bar by a cord from a hook, as in Fig. 80, or by a prop underneath, as in Fig. 79, the whole bar is supported. If the center of

gravity is not supported, the whole body falls. And if the body falls, it falls in the direction of a straight line from its center of gravity toward the center of the earth.

d. Take the case of a body, *BD* (Fig. 81), hung by one corner upon a hook, drawn to one side and released. It will swing to and fro, and finally come to rest with the corner *D* in a vertical line below the hook. Suppose it to be drawn aside, and held with its sides vertical. Let *c* be the center of gravity; then *cg*, a vertical line, represents the gravity on the whole body, and there is no force directly upward to balance it. But we may resolve it into two components, one of which is *cb* and the other *cd* (§ 63, *c*). Now *cb* pulls directly against the hook and is balanced by its reaction (§ 9, *g*). But *cd* is not balanced, and would produce motion. Hence when the body is released, *c* swings to the right. But when *c* is directly under *B*, gravity is wholly balanced by the reaction of the hook. Then there is no component (§ 62, *d*) *cd*, that is to say, there is no longer any force to pull the body to right or left.

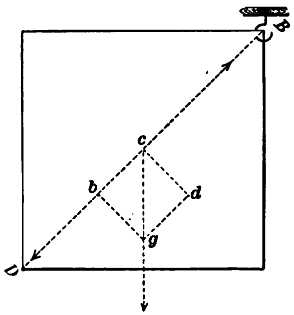

Fig. 81.

Experiment 36. — *Object.* To find the center of gravity of a piece of thin board of uniform thickness.

BB (Fig. 82) represents the board. Several holes made with an awl near the edges are designated by numbers.

S represents a support, into which has been driven a slender and headless wire nail to support the board. The holes must be large enough to let the board swing freely on this nail.

A bullet, *b*, is suspended from the nail by a thread. The loop for the nail must be large enough to let the bullet adjust its center exactly in a vertical line through the *center* of the nail.

Proceed as follows: Slip the nail through a hole, and let the board swing without rubbing against *S*. Hang the plumb line (the bullet and

thread) upon the nail, just far enough in front of the board to swing without touching it. When the board and plumb line have come to rest, make a distinct mark with a slender pencil point exactly behind the thread near the bottom of the board.

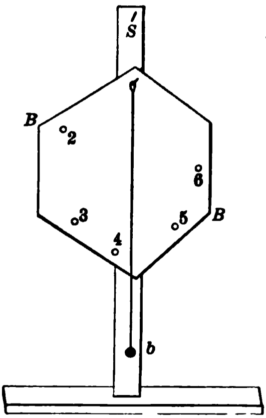

Fig. 82.

Remove the board from the nail, and draw a line carefully through the pencil mark and the *center of the hole*. The center of gravity of the board is somewhere in the direction of that line. Why?

Repeat these operations for each of the several holes. All the lines thus drawn should intersect at one point. The center of gravity of the board is half way through the thickness at that point of intersection.

e. A vertical line through the center of gravity of a body is called the *line of direction*. It is the direction in which the body falls if not supported.

If the line of direction falls outside the boundaries of the base of the body, the body will topple over. To study this case, stand a rectangular piece of wood upon the table with its edge toward you. Its section is represented by *A* 1 (Fig. 83), its center of gravity by *c*. Drive a pin at *c*; hang from it a small button by a fine thread, to show the line of direction, *ca*. Gently push the top of the block; it will turn on its edge *a*, *c* will swing over, and the foot of the line of direction will approach *a*. But the block will return to its upright position unless the foot of that line passes *a*. The moment that occurs, as represented by *A* 2, the block falls.

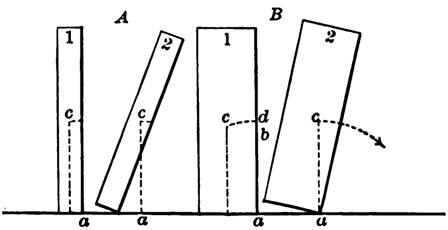

Fig. 83.

f. Next stand the block with its broad side toward you (*B* 1), and tilt it edgewise. It will need to be tilted much farther in order to carry the foot of the line of direction to *a*. You must push with greater force than when the block went sidewise, because you have to *lift the center of gravity*, which is equivalent to the whole weight of the block, through the vertical height *bd*; whereas in the other case you must lift it a much shorter distance. In other words, you must in this case do more work (§ 14, *a*). When the center of gravity, *c*, passes the vertical line through *a*, that moment it will begin to descend. The whole body will topple over.

g. When the center of gravity is supported, the body is said to be *in equilibrium.*

If a body cannot be tilted in any direction without raising its center of gravity, it is said to be *in stable equilibrium* (Fig. 83, *A* 1, *B* 1).

If to tilt a body in any direction would require the center of gravity to descend, the body is said to be *in unstable equilibrium* (Fig. 83, *B* 2).

If a body can be tilted in all directions without raising or lowering its center of gravity, it is said to be *in neutral equilibrium.* This is the case when the support is applied at the center of gravity.

h. It is a common observation that tall and slender objects are more easily overturned than those which are low and broad. We use the word *stability* to compare bodies in this respect.

The stability of a body is measured by the work which must be done to lift its center of gravity to a point directly over the boundary of its base. A study of Figs. 84 and 85 will make this point clear. To overturn either of these bodies requires the center of gravity, *c*, to describe an arc with *a* as a center; and to bring it directly over *a*, it must be lifted through the vertical height *vh*. The work to be done will

vary directly as that height (§ 14, *b*). The greater this work, the more stable is the body.

Or, we may put it in another way. Since *vh* is greater or less, just in proportion to the angle *cah*, the work done to

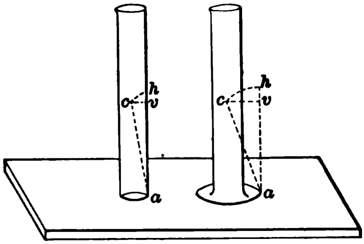

Fig. 84.

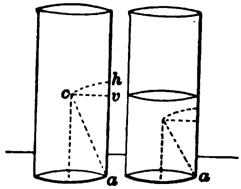

Fig. 85.

overturn a body varies directly as that angle. Hence the stability of bodies is proportional to the angles through which they must be tilted to overturn them.

The broader the base and the lower the center of gravity, the more firmly will a body stand. Why?

67. **Studies.** — 1. A passenger crosses the deck of a ship which is 45 feet wide, and while he is doing so the ship goes a distance of 100 feet. Construct a diagram, and find the actual distance the passenger went.

2. Two persons are on a seesaw, 12 feet apart. The weight of one is 90 pounds, of the other, 120 pounds. Neglecting the weight of the seesaw, find how far from the support of the seesaw each would sit.

3. Two men, A and B, carry a mass of 60 kg. by each holding one end of a bar 2.5 m. long, on which the mass is hung at a distance of 100 cm. from A; how much of the mass does each support?

4. Suppose a beam (*ab*, Fig. 86) is under the influences of several forces (-3, $+4$, -5, $+2$, -6 dynes[1]), arranged along its length at distances 4, 6, 8, 12, 14 cm. from some fixed point of reference, *c*. Find the resultant (§ 64, *c*, *d*).

1st. Its magnitude $= -3 - 5 - 6 + 4 + 2 = -8$ dynes.

2d. Its direction is $-$, that is to say, downward.

3d. Its point of application is found as follows: $-3 \times 4 + 4 \times 6 - 5 \times 8 + 2 \times 12 - 6 \times 14 = 88$ cm.; its distance from $c = 88 \div 8 = 11$ cm.

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[1] The signs + and − are used to show opposite directions.

Measure 11 cm. from c, and we find r, the point of application of the resultant of all the forces.

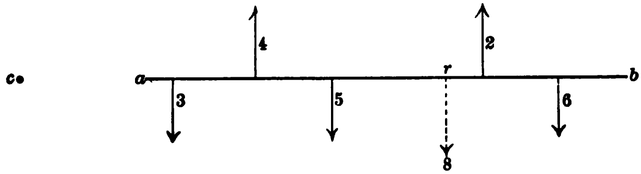

Fig. 86.

5. How would you find the center of gravity of a cardboard triangle? Where is the center of gravity of a plain gold finger ring?

6. AB (Fig. 87) represents a rod to which another, BC, is fastened by cords, one end directly to B, the other end, C, to D. It will be found that this combination will fall from any point of support, such as the edge of a table top. But if you will hang a heavy mass, m, at C, the combination of rods will not fall. What is the explanation?

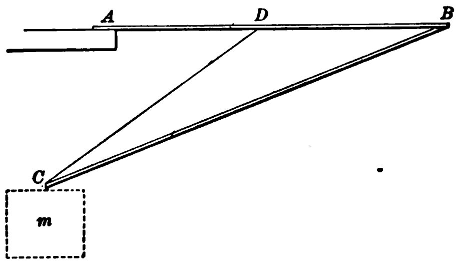

Fig. 87.

7. In addition to the fact that it is more graceful in appearance, is there any reason why a monument like that at Bunker Hill or Washington should taper toward the top?

8. In walking, when one foot is lifted, the body is at the same time thrown forward. Why is this necessary? Why are the arms thrown forward when there is danger of falling backward?

MOTION IN A CIRCLE — THE PENDULUM.

68. **Motion in a Circle.** — *a.* If you will fix a ball or a stone to the end of a string, and whirl it in a vertical circle, you will feel it pulling away from the hand, all the way around. Try it;

and ask yourself why it should pull upward, instead of falling, when above the hand. Swing it again, but with greater velocity; you will find that it pulls with greater strength than before. Swing a heavier ball with the same length of string, and the same velocity as nearly as possible; you will find that it, likewise, pulls with greater strength. If let go, in what direction will it fly? Try it.

In what direction does it pull? Why should the strength of its pull increase with its velocity and its mass? The object of the following study is to answer these questions.

b. In Fig. 88, *b* represents the ball, *Hb* the string. It is the action of the hand, through the string, that starts the ball, and a repetition of that action, now and then, will keep it going.

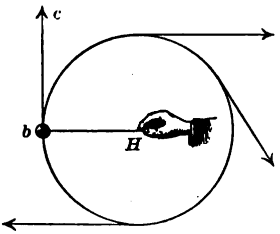

Fig. 88.

But at the *moment* the ball has reached *b* it is going in the direction *bc*, and, left to itself, it would go on in that straight line (§ 4, *c*). It is pulled out of that line by the string. The ball is subject to these two forces, — *the impulse from the hand,* in a straight line which is tangent to the circumference; and *the pull of the string,* which is always toward the center.

c. So, likewise, two forces are involved in every motion in the circumference of a circle. That which starts the body is called the *tangential force.* That which pulls the body out of a straight line is called the *centripetal force.*

d. Now see how the motion in the circular path is the resultant of the tangential and centripetal forces. Thus:

When the ball, swinging around the circle, is at *A* (Fig. 89), the tangential force is toward *B* and the centripetal force is toward *C.* The joint action of the two must drive the ball diagonally between their directions (§ 62, *d*). Take *Ad* for the distance it actually goes in a very small fraction of a second,

so small that the arc will be practically a straight line. Drop the perpendiculars *dh* and *de*. Then one adjacent side, *Ah*, of the parallelogram represents the tangential force, and the other, *Ae*, the centripetal force. Such a pair of components on the ball at every moment drive it along its circular pathway.

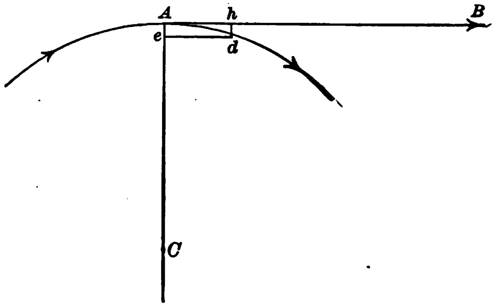

Fig. 89.

e. But this centripetal force was only one part of the stress (§ 22, *a*) in the string in the experiment (*a*); the other part was the reaction of the ball. The ball pulled against the hand as much as the hand pulled against the ball. This reaction is the pull which you felt.

The reaction of the revolving body is called the *centrifugal force*. Of course it and the centripetal force are equal (§ 9, *d*).

f. The effect of centrifugal force may be illustrated easily. Try it as follows: To the handle of a small pail, partly filled with water, tie a strong cord. Grasp the cord, and swing the pail fearlessly in a vertical circle. The centrifugal force will balance the gravity of the water so that not a drop will fall, even when the pail is bottom side up overhead.

g. Centrifugal force is illustrated in many common affairs. Carriages, in rapid motion around a corner of the street, are in danger of being overturned by this force. Water and earth fly off the rim of a carriage wheel when it is turning rapidly. The circus horse and rider both lean toward the center of

"the ring" so that gravity may balance this force. Grindstones sometimes burst when turned swiftly; the centrifugal stress of their outer parts becomes so great that the cohesion (§ 47, *a*) of the stone cannot balance it. Massive fly wheels are sometimes torn to fragments by the same stress.

h. The centrifugal force by which such effects are caused may be computed if we know the *mass* of the body, its *velocity*, and the *radius* of the circle in which it revolves.

For if we use initial letters, we may write:[1]

$$C = \frac{Mv^2}{r}.$$

Examples. — 1. If a ball whose mass is 1.5 pounds is whirled in a circle by means of a cord 2 feet long, at a rate of 20 feet per second, how much will it pull against the hand? By substituting given values,

$$C = \frac{1.5 \times 20^2}{2} = 300 \text{ poundals.}$$

Or, since 32.16 poundals is the "weight of a pound," we have

$$\frac{300}{32.16} = \text{the weight of } 9.2 \text{ pounds.}$$

If the cord is not strong enough to sustain the weight of 9.2 pounds, it will be broken.

2. A wheel is turning swiftly on its axis. What is the centrifugal force of 5 pounds of the rim, if its radius is 3 feet and it makes 90 revolutions a minute?

In this case the mass and the radius are given, but the velocity must be computed. It is the distance around the circumference 90 times, divided by 60, or $2\pi \times 3 \times 90 \div 60$.

i. By translating the expression $C = \frac{Mv^2}{r}$, we obtain the following laws of centrifugal force:

1. *The centrifugal force varies directly as the mass of the revolving body, if the velocity and the radius of the circle remain the same.*

2. *The centrifugal force varies directly as the square of the*

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[1] The proof of this formula for one unit of mass, M, may be found in Carhart's *University Physics*, p. 30.

velocity of the revolving body, if the mass and the radius of the circle are unchanged.

3. *The centrifugal force varies inversely as the radius of the circle in which the body revolves, if the mass and its velocity are unchanged.*

j. As the earth rotates on its axis, every body on its surface is carried completely around once in every 24 hours. The diameter of the circles they traverse vary with the latitude. At the poles it is zero; at the equator it is about 8000 miles. On this account bodies everywhere, except at the poles, are urged by centrifugal stress to fly from the earth's surface.

This centrifugal force partly balances the attraction of the earth (§ 52, *b*). On this account the weight of a body is less than it would otherwise be.

69. **The Pendulum.** — *a.* Any body if suspended from a fixed support so that it can swing freely, is a *pendulum.* The most usual form of the pendulum is a massive ball, or "bob," hung by a slender rod or cord from a firm support. An ideal form consists of one material particle suspended by a weightless thread; this is called the *simple pendulum.* Of course, practically, there is no such pendulum. The nearest approach to one is a small lead ball suspended by a very slender thread. The explanation of the motion of a pendulum is much simplified by supposing it to be a simple pendulum, as it would be if all its mass were concentrated at one particular point (§ 66, *c*).

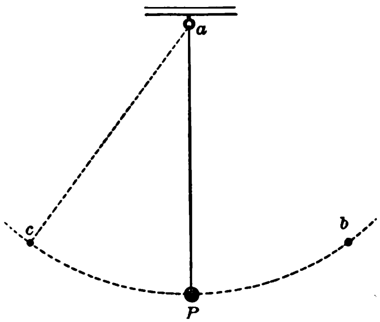


Fig. 90.

b. Let *P* (Fig. 90) represent an approximately simple pendulum bob suspended from *a*. If pulled aside to *c* and released,

it will swing to and fro in the arc *cb*, but its path will gradually shorten until, at length, it stops at *P*.

The swing of the pendulum through the length of its arc once, is called a *single* or *simple vibration*. The swing of the pendulum through the length of its arc and back again, is called a *complete vibration*. A vibration of either kind may be measured from any point in the arc. Thus from *c* to *b* to *c*, or from *P* to *b* to *c* to *P*, is one complete vibration. The number of degrees in one half its arc, as *cP* or *Pb*, is called the *amplitude*.

The time required to make one complete vibration is called the *period*. The period is fully defined in this way: The time between two *successive passages* of the pendulum, through *any given point, in the same direction*.

Experiment 37. — *Object.* To discover the conditions on which the period of a pendulum depends.

Apparatus. Three lead balls for bobs, two of them with equal diameters, about 2 cm., and one of them larger than these. A wooden ball of the same size as the smaller lead balls. A support from which to suspend the balls. Fig. 91 represents a simple and satisfactory pendulum support, firmly clamped upon the edge of a table. Good corks fit the holes in the projecting arm. The slender thread of the pendulum is to be passed up through the hole in *L*, and then drawn well into a deep cut made lengthwise of the cork with a sharp knife. The cork is then pressed into the hole. By this means the pendulum will be firmly fixed, and yet its length can be readily changed, simply by pulling the thread through the cork.

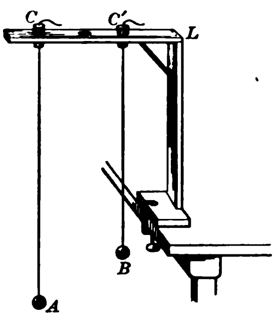


Fig. 91.

Operations. 1. To learn whether the period depends on the length of the pendulum.

Hang two pendulums, *A* and *B*, just alike in all respects except in length. Pull them aside an equal distance, and release them both at the same moment. You can judge by the eye whether they make a complete vibration in equal times. If they do not, you can infer that the period of a pendulum does depend on its length.

2. To learn whether the period depends on the mass of the pendulum.

Hang the larger lead ball beside one of the smaller ones. Make the two pendulums swing, varying the length of one until they swing in equal times. Now find their lengths by measuring from the bottom of the cork to the middle of each ball. Are the pendulums alike in all respects but mass? Does the period of a pendulum depend on its mass?

3. To learn whether the period depends on the material of the pendulum.

Hang the wooden ball beside the lead ball of the same diameter, and proceed in all respects as in the last experiment.

4. To learn whether the period depends on the amplitude.

Make the two pendulums swing in the same time. Pull them aside unequally; release them at the same moment, and judge whether the length of the arc makes any difference in the length of the period.

Finally write a statement as to the conditions on which the period of a pendulum depends, according to your experiments.

Experiment 38. — *Object.* To discover the law that connects the period of a pendulum with its length.

1. The length of the pendulum must be measured as accurately as possible. Measure the diameter of the ball by the method in Experiment 2. Suspend the pendulum, and measure the thread from the bottom of the cork to the top of the ball. Then add the radius of the ball to the length of the thread. About 100 cm., or about 36 inches, is a good length to choose for the longer pendulum.

2. The time of one complete vibration (b) must be found as accurately as possible. To find it, draw a heavy straight line on a sheet of paper, and fix the paper to the pendulum support with the line vertical, and exactly behind the pendulum bob when it is at rest. Set the pendulum vibrating *in a small arc.* With a watch in hand and the eye in front of the resting place of the pendulum, count the passages of the bob across the vertical line in the same direction, made in 60 or more seconds. Divide the number of vibrations by the number of seconds for the time of one vibration, or the period. Evidently the longer the time chosen for the count, the smaller will be the error in the period. Why?

Repeat with another pendulum much longer, and with a third much shorter, than the first. Record each value as follows:

Let l stand for the length of the pendulum, n for the number of complete vibrations in —— seconds, and t for the time of one.

l	n	t	t^2	$\frac{l}{t^2}$

After the values of l and n have all been obtained, compute the value of t for each set. You should find that the longer pendulum has the longer period, but that the length and period do not change in the same proportion. But if you will square the values of t, and then divide the lengths, l, each by the corresponding t^2, you should find that the quotients are equal, or nearly so. Now $\frac{l}{t^2}$ could not be a constant value unless the numerator and denominator, l and t^2, change together in the same proportion. Hence the square of the period varies as the length.

c. The following law connects the periods of vibration with the lengths of pendulums:

The squares of the periods of two pendulums of different lengths, at the same place, vary directly as the lengths.

This law is proved by Experiment 38. That experiment shows by the values in the last column of the tabulated results that any two lengths, when divided by the squares of the corresponding periods, yield equal quotients. Thus:

If T stands for the period of one pendulum whose length is L, and t for that of another whose length is l, we have:

$$\frac{L}{T^2}=\frac{l}{t^2}.$$

But when two fractions are equal, as in this case, their numerators are directly proportional to their denominators, as explained in Appendix II. Hence we have either

$$L : l :: T^2 : t^2 \text{ or } T^2 : t^2 :: L : l.$$

If one pendulum is four times the length of another,

$$T^2 : t^2 :: 4 : 1; \text{ whence } T : t :: 2 : 1.$$

Therefore its period is twice that of the other. Again, if the lengths, L and l, of two pendulums are as 1 to 9, then their periods, T and t, are as 1 to 3.

Example. — A pendulum to make one single vibration per second is very nearly 39.1 inches long; what must be the length of one to vibrate half seconds? Write $1^2 : (\frac{1}{2})^2 :: 39.1 : l$, and find the value of l.

Ans. 9.8 nearly.

d. To explain the motion of the pendulum, make a diagram (Fig. 92) showing a simple pendulum, *cp*, just ready to begin its swing; while a few points through which it will pass are shown by the letters and numbers on the arc. Draw vertical lines downward to represent gravity. Resolve (§ 63, *d*) gravity at *p* into the two components, *pa* and *pb*. The pull *pa* is balanced by the opposite pull of the thread *pc*, but *pb* is unbalanced and urges *p* toward *o*. Resolve gravity at 1, *o*, 2, *p'*, in the same way; it will be seen that the force *pb* is less at 1, is zero at *o*, pulls back toward *o* at 2 and at *p'*. It will also be seen that the pull at *p'* is equal to *pb*, if the arc *op'* is equal to arc *op*.

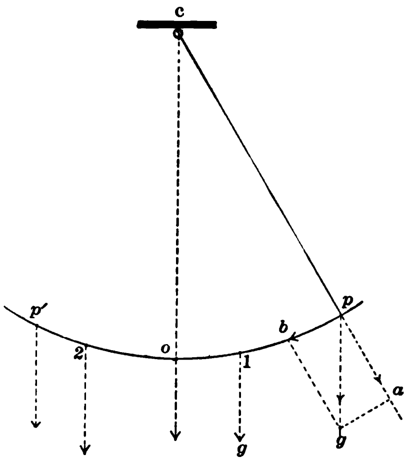


Fig. 92.

The motion, therefore, is accelerated (§ 12, *b*). Its acceleration is positive to *o*; it is negative from *o* to *p'* (§ 55, *c*). What *p* gains in the first half of the swing is wholly lost in the second half. The pendulum stops at *p'*, and then returns to *p* by the same forces in the opposite direction. So it appears that the vibration of a pendulum is produced and kept up by gravity and the reaction of the support.

e. Newton obtained an equation which expresses the relations of the time of one complete vibration of the pendulum to all the values on which it depends. If the amplitude is very small, the equation is written:

$$T = 2\pi\sqrt{\frac{l}{g}}.$$

This formula shows that *the time of one complete vibration of a pendulum of given length, varies inversely as the square root of gravity.*

f. Since π is a constant value, 3.1416, Newton's equation shows that if we can find the values of T and l, we can compute the value of g, or the acceleration of a falling body.

Experiment 39. — *Object.* To find the value of g by means of a pendulum.

Proceed as directed in Experiment 38 to find the length and the period of a given pendulum. Measure the length in centimeters; 1 m. is a good length to use. Count a large number of complete vibrations in order to find a more accurate value of the period. Repeat the measurements and obtain the average length and period. Let n stand for the number of vibrations made in N seconds, and t for the period. Let l stand for the length of the pendulum. Record the values found, thus:

Trials.	Observations.			Computations.			
	n	N	l	t	Average t	Average l	g
1	......	......	......	......			
2	......	......	......	......	......	......	......
etc.	......	......	......	......			

Finally, substitute your average values of t and l in Newton's equation, and compute g.

g. We have so far supposed the pendulum to be simple (*a*). Practically all pendulums are compound, and the explanation (*c*) of their motion is more complex.

Gravity pulls every particle of the pendulum (§ 66, *b*). So each particle would be an independent pendulum if all were not bound together by cohesion (§ 47, *a*). Those near the lower end are longer and would vibrate more slowly; those near the upper end are shorter and would vibrate more swiftly. There must be a particle at some place between, where these two actions are balanced, and the time of a vibration of the whole pendulum is the time of vibration of that particle.

The location of that particle whose period is not changed by the action of other particles is called the *center of oscillation.* Can the location of this point be found? Try it as follows:

Obtain a bar of wood of uniform size, 1 m. long, about 5 cm. wide, and 1 cm. thick. Cut a groove across the middle of one end. Make a small wire staple, with sharp points, and drive it in astride the groove until the *inside of the bend* is flush with the end of the bar. Hang the bar by the staple upon a piece of stiff knitting needle inserted in a support. The bar is a pendulum with its point of suspension at the end. Fix a small ball on the end of a long thread; pass the thread over the wire in front of the bar and fasten the other end to a block upon the table. By winding the thread on the block, or simply sliding the block, the length of this simple pendulum may be changed. Make its length equal to that of the bar, and start them both at the same time; the bar swings faster than the ball. Lift the ball to the middle of the bar and vibrate them again; the ball swings faster than the bar. Find by trial at what height the ball must be placed so that the two have the same period. The ball is then the bar's *equivalent simple pendulum*; and a point in the bar, on a level with the middle of the ball is, approximately, the center of oscillation of the bar. Its distance from the suspension should be two thirds the length of the bar.

The centers of suspension and oscillation are reversible. Drill a hole through the bar at two thirds of its length from the staple end. Hang the bar by passing the wire through this hole and you should find that the bar vibrates with the same period as before.

The center of oscillation is in all cases below the center of gravity (§ 66, *b*); but in pendulums with small bobs and slender suspensions its distance below the center of gravity of the bob is very small. All the values we have met in describing the pendulum, — the length, the period, the laws, and the formula, — refer to this equivalent simple pendulum.

h. We have found (Experiment 37) that the time of one vibration does not depend on the amplitude. This fact is expressed in the *law of equal times*, or *law of isochronism:*

The period of a pendulum is practically constant for all amplitudes less than about 20°.

i. The pendulum is used to measure time. So long as the length of a pendulum is not changed, its vibrations will follow

one another in equal intervals of time. The common clock is simply an instrument by which the motion of a pendulum is kept up by a weight or spring, and the time occupied by any number of its vibrations shown by the position of "hands" on a graduated dial.

By looking at the "works" of a clock, one can see how the pendulum compels the wheels and the hands to move uniformly; it does this by letting only one tooth of a wheel escape with each vibration.

A pendulum that makes one complete vibration in 2 seconds, or one single vibration in 1 second, is called a *seconds pendulum.* Its length in the latitude of New York is about 39.1 inches.

But the same pendulum will not have exactly the same length in summer and winter, because the length of a body is increased by heat and diminished by cold. Hence a clock will lose or gain time as the temperature changes, unless the length of the pendulum can be adjusted. Commonly, the bob can be raised or lowered by a screw. In astronomical clocks the pendulum is made of two metals, so fixed that the heat lengthens them in opposite directions equally, and thus leaves the length of the pendulum unchanged.

70. **Studies.** — 1. If a carriage and its load — a mass of 500 pounds — goes at the rate of 5 miles per hour, and turns a corner of the street on the arc of a circle of 15 feet radius, how many poundals of force urge it to upset? This would be equal to the weight of how many pounds where the acceleration is 32.1 feet per second? By what is this centrifugal stress balanced if the carriage is not overturned?

2. Why must a skater who goes swiftly around a circle lean continually toward the center?

3. A pendulum is wanted for a mantel clock in New York, which will vibrate once in a half second; how long shall it be made?

4. A pendulum clock is found to be losing time; what change would you make in order to correct it? Explain.

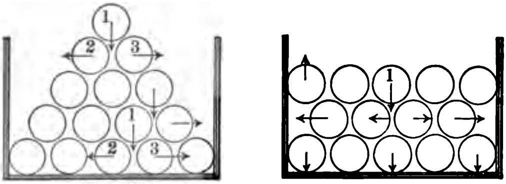
5. A pendulum clock, keeping correct time in Chicago, is carried to New Orleans. Would it need to be "regulated"? Why? How?

VI. FLUIDS AT REST.

PRESSURE OF FLUIDS.

71. **The Transmission of Pressure.** — *a.* In such fluids as water and air the molecules act like almost perfectly smooth bodies. They slide or roll over and around one another, not with perfect, but with almost perfect, freedom. The freedom of motion among the molecules of a substance is called *mobility.*

b. On account of their mobility fluids yield to the slightest stress, unless they are held firmly by supporting walls on all sides, and in that case they transfer to the walls the stress to which they cannot yield. It is possible to pile up balls with



I II

Fig. 93.

rough surfaces, as shown by Fig. 93, I, because the friction of their surfaces keeps them from sliding under the pressure of those above. The weight of 1 is directed downward between 2 and 3, but 2 and 3 are too rough to slide from under it. Smooth glass balls could not be built up in that way. 2 and 3 would be pushed sideways by the weight of 1, and the same action would occur on those below. The balls would roll down against the walls of the box and press against them as in Fig. 93, II.

c. Now suppose a tight vessel with a small opening on the top to be completely filled with water, and that we can see the molecules. Suppose a pressure equal to the weight of 10 g. to be put upon the molecule at *P*. If there is no viscosity, the only resistance to the motion of the molecules is exerted by the walls of the vessel. The pressure of the 10 g. on *P* would be downward between the molecules below, and cause them to press sideways between others, and these in other directions between others, and thus the action is equally transmitted in every direction until it is balanced by the walls of the vessel at every point on the bottom, sides, and top.

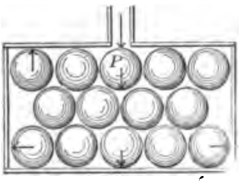


Fig. 94.

d. The fact that fluids do thus transmit pressure was first observed by Pascal about two hundred years ago, and it is known as Pascal's law. It may be stated as follows:

When a fluid is confined in a vessel, and a certain amount of pressure is exerted on a given area, the same amount is transmitted in all directions, to every equal area, everywhere in the fluid, and on the walls of the vessel.

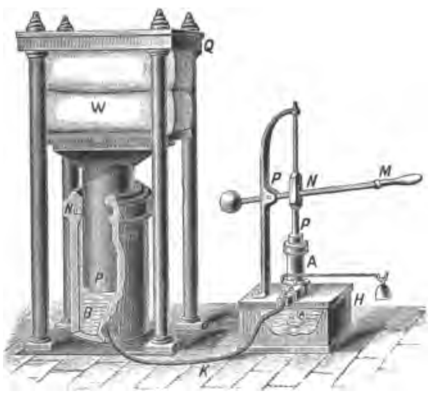


Fig. 95.

An illustration of the law is found in the inflation of a football. The pressure which pushes the air in pushes the rubber walls outward at every point.

e. The *hydrostatic press* is a machine (§ 24, *a*) by which Pascal's law is applied to produce great pressures. It is shown in Fig. 95. It consists

of two cylinders, A and B, one larger than the other, connected at the bottom by a tube, K. They are provided with solid pistons, P and p. When p is lifted, water is pumped into the small cylinder; when p is pushed down, that water is driven into the large cylinder, and a valve prevents its return. The pressure of p is transmitted by the water to P, which is pushed up.

According to Pascal's law, the upward pressure against P must be as many times greater than the downward pressure by p, as the area of the under surface of P is greater than that of p. If the area of P is 50 square inches and that of p is .5 square inches, the weight of 1 pound on p would balance the weight of 100 pounds on P. That is to say, the mechanical advantage (§ 25, *d*) is found by dividing the area of the larger piston by that of the smaller.

Examples. — A man puts a pressure equal to the weight of 75 pounds on p. If the areas of p and P are .8 square inches and 100 square inches respectively, how much pressure will P exert?

If the man's pressure is applied at M on the lever of the press (Fig. 95), and if PM is 4 feet and PN is 1 foot, what pressure do the goods at W sustain? *Ans.* The weight of 37,500 pounds.

f. The universal law of machines (§ 24, *e*) holds good in the hydrostatic press. For if P is raised, it is lifted by the water driven out of A into B. If the area of P is, say, 20 times that of p, then that water can raise P only $\frac{1}{20}$ as high as p descends. So that

$$\text{Power} \times \text{power distance} = \text{weight} \times \text{weight distance (§ 24, } e, f).$$

72. **Pressure within a Fluid.** — Fluids are subject to the law of gravitation (§ 51, *d*), and the earth-pull on any portion of a fluid causes a downward pressure on that which lies below. The downward pressure at any point will be greater or less just in proportion to the depth of the point below the surface. It must be carefully borne in mind that the amount

of pressure at any point is wholly unaffected by the depth of the water below that point.

But if there is downward pressure at any place in a fluid *at rest,* there should be equal pressures in other directions to balance it (§ 71, *b*). Do such pressures upward and sideways really exist in a vessel of water or in air?

Experiment 40. — *Object.* To test for the pressures in various directions in a vessel of water.

In Fig. 96, *Hpg* represents a Hall's pressure gauge with which to explore the interior of the water contained in a large vessel. It consists of a thistle tube funnel, *g*, with its mouth covered with very thin sheet rubber, tied so tightly as to make a water-tight joint; a glass tube, *H*, and a rubber tube to connect the two. *H* should be wetted inside; have a little column of colored water at *i*; its end then put into *p*, and, finally, supported in horizontal position by a clamp.

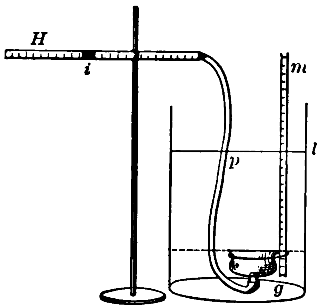


Fig. 96.

The index *i* will show whether pressure is exerted against the face of *g*. Try it by gently pressing the rubber with the finger. Narrow strips of gummed paper equally distant along *H*, or a meter bar bound alongside of *H*, will help to measure the motion of *i*, and thus to judge of the amount of pressure.

The gauge, *g*, may be fastened to the end of a meter bar, *m*, by a rubber band, and then sunk in the water with its face up. Note the distance of the face below the surface, *l*, and also the distance through which *i* moves. This distance represents the *downward* pressure at that level.

To test for upward pressure, strap *g* to *m* with its face down, and sink it to the same level as before. Test also for pressures sidewise and slanting, by strapping *g* to *m* horizontally or obliquely and sinking it to the same level. Test for pressures at other levels by sinking *g* to greater or less distances.

Examine the records of your work, and state:

1. The *facts* observed in regard to the directions of water pressure at a given distance below the free surface.

2. The *inferences* in regard to the relative amount of pressure in different directions and at different depths.

Experiment 41. — *Object.* To test for the pressures in various directions in air.

Use the same pressure gauge as in the preceding experiment. Holding it in the air, there is no indication of pressure. Try it. But remember that the air is on both sides of the rubber, and if there be any pressure on one side it may be balanced by the pressure on the other. To detect pressure we must take air away from one side, so as to leave that on the other side free to push the rubber if it can. Remove the index *i*; put the lips to the end of *H*, and gently suck the air out, watching the rubber for indications of pressure. Test for pressure in various directions by turning the face of *g* upward, sideways, and slanting.

State the *facts* revealed by your tests. Can you *infer* anything in regard to the relative *amounts* of pressure in various directions?

Experiment 42. — *Object.* To find the relation between the pressure on a given area and the depth of that area below the surface of the fluid.

Apparatus. A tall glass jar or cylinder, *A* (Fig. 97), 30 to 40 cm. deep, to be filled with water. A bent glass tube, *t*, with one arm about 8 cm., and the other about 40 cm., long. A meter bar, *m*. Mercury.

Manipulation and Notes. Fix *t* against the side of *m* by rubber bands. Put mercury in *t* to fill both branches to equal heights about 5 cm. above the bend. Any pressure upon the mercury at *a* will push the mercury up at *b*, and the difference in the levels of *a* and *b* will be proportional to that pressure.

Insert this pressure gauge into the water in *A* with its bend at the bottom of the jar. Note the depth of the mercury surface in the short branch below the surface of the water in *A*, and also the height of *b* above *a*. Read the scale to the nearest .1 cm.

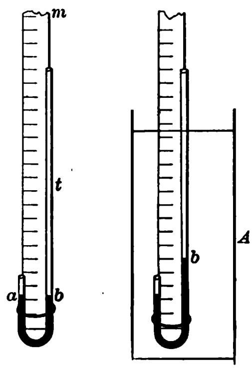


Fig. 97.

Raise the pressure gauge, and note again the depth of *a*, and the distance between the levels of *a* and *b*. Repeat the observations at another still higher level.

Inference. Take two of the depths and their corresponding pressures, and see if you can write the four values so as to form a true proportion. See whether each pair of depths are proportional to the corresponding pressures. Then state the relation thus revealed. (Appendix II.)

73. Pressure on the Bottom of a Vessel. — *a.* If the base of a vessel is horizontal, and its walls vertical, as shown in sec-

tion by Fig. 98, the weight of the fluid which it contains must be supported by the base. The walls will support the side pressures, but none of the downward pressure, any more than if the fluid were a solid, with perfectly smooth sides, slipped into the vessel. The pressure on the base, *ab*, is the weight of the fluid, *abh*.

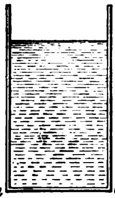


Fig. 98.

The pressure on the horizontal base of a vessel with vertical walls is just the weight of the fluid which the vessel contains.

b. Suppose the vessel to be a cylinder containing water. Suppose the diameter of the base, *ab*, to be 2.5 cm., and the depth of the water, *hb*, to be 8 cm., and that we desire to know the pressure which the base sustains.

We can easily find the volume of the water in *abh*.

$$\begin{aligned}
&\text{Volume} &&= \text{area of the base} \times \text{the height};\\
&\text{area of base} &&= \tfrac{1}{4}\pi \times \text{square of the diameter};\\
\therefore\ &\text{volume} &&= \tfrac{1}{4} \times 3.1416 \times 2.5^2 \times 8 = 39.27 \text{ cc.}
\end{aligned}$$

But the mass of 1 cc. of water, at 4° C., is approximately 1 g.; so the total mass of water in our vessel is approximately 1 g. × 39.27, or 39.27 g., and the pressure on the bottom is *the weight* of this mass (§ 52, *e*).

Notice that the numerical work in this example may be expressed briefly as follows: Mass of 1 cc. of water × *area* of the base × *height* of the water.

c. The work would be the same for any other fluid, using the mass of 1 cc. of that fluid as we have used the mass of 1 cc. of water. But the mass of 1 cc. is the *density* of any substance (§ 6, *b*); so that in general:

The pressure on the base = density × area of base × height of fluid; or, if we use letters for words:

$$P = d \times a \times h.$$

d. We must not forget that the value of P, when thus found, is really mass, and not pressure. The pressure is the weight of this mass. Hence the unit of pressure is the gravitational unit. It is either "the weight of a gram," or "the weight of a pound" (§ 52, *e*). For the pressure in absolute units, either dynes or poundals, we should have:

$$P = d \times a \times h \times g.$$

Example.—A flat-bottom bottle, with straight, vertical walls, contains mercury 10 cm. deep. The bottle is 5 cm. in diameter, and the density of mercury is 13.6 g. per cc.:

1. What mass of mercury exerts pressure on the base of the bottle?
2. What is the pressure on the base in gravitational units?
3. What is the pressure on the base in dynes in the latitude of New York?
4. What is the pressure on the base in poundals in the latitude of New York?

74. **Pressure on Any Surface.**—*a.* The pressure of a fluid on any plane surface whatever in the fluid, as well as on the base of the vessel, may be found in the same way, by the use of the same formula.

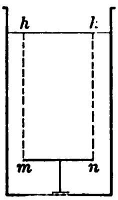


Fig. 99.

Take the case of a horizontal sheet of metal (mn, Fig. 99) upheld in water. The downward pressure of the water upon it is just the weight of that which is vertically over it, or the weight of the column whose base is mn and whose height is mh. It is $d \times a \times h$ as before.

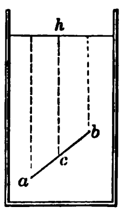


Fig. 100.

b. Take the case of a surface which is not horizontal within a fluid (ab, Fig. 100). Again, it is only the fluid vertically over the surface that exerts the downward pressure upon it. The depth of the fluid is not the same all over ab, and of course the pressure varies; but, as a whole, it is just the same as it would be if all points received the same pressure as the middle point, c. The increase on account of the greater depth of the

lower half, *ca*, is just balanced by the decrease on account of the lesser depth of the upper half, *cb*. So the height of the column of fluid that presses on *ab* is *ch*, and the pressure is the weight of the column whose base is the area of *ab*, and height *ch*; it is $d \times a \times h$ as before. Remember that *h* always stands for the height of the fluid above the *middle point* of the surface which receives the pressure.

c. The pressure on the bottom of a vessel is $d \times a \times h$, no matter what the shape of the vessel may be. Of course vessels represented by *C*, *B*, *A* (Fig. 101), will hold very different quantities of water if filled to the same height. But if they are of equal size at their bottoms, the downward pressures on their bottoms will be equal. This fact is proved by the following experiment:

Fig. 101 represents the essential parts of Haldat's apparatus. It consists of three or more vessels of different shapes, *A*, *B*, *C*, with equal bases, and a tube, *T*, bent twice at right angles, containing mercury. At one end of *T* there is a reservoir, *r*, and mercury fills the tube and reservoir to the height shown by the dotted line.

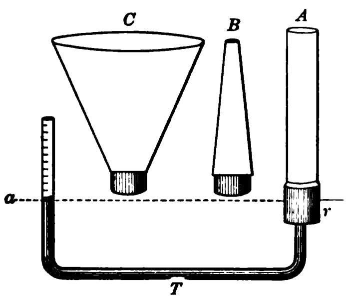


Fig. 101.

The vessels are open at the bottom, but each can be screwed upon the top of *r*, and then the surface of the mercury there becomes its base.

Pressure on the mercury in *r* will push the mercury up the tube at *a*, and the rise at *a* will be proportional to the pressure.

A*, *B*, and *C*, one after another, are screwed to *r* and filled with water to the same height. The mercury at *a* is lifted just as far by the pressure in one vessel as in another. This shows that *the downward pressure of a fluid on the bottom of a vessel is independent of the shape of the vessel.

d. Provided the area at the base be the same, it makes no difference how small a diameter the tube above it may have; the pressure on that base will depend solely on the height of

the column above it. From this fact arose the interesting "hydrostatic paradox:" *Any quantity of liquid however small may exert any pressure however great.*

e. The only things that affect the pressure, P, of a fluid at rest, on any surface which it touches, are:

1. The area of the surface pressed upon . . . . a.
2. The depth of the middle point of this surface . . . h.
3. The density of the fluid . . . . d.
4. The local force of gravity . . . . g.

And in every case it is true that

$$P = d \times a \times h \text{ gravitational units;}$$
$$P = d \times a \times h \times g \text{ absolute units.}$$

In computing the value of P remember that density, d, is the mass of any unit of volume, — the cubic centimeter, the cubic inch, or the cubic foot, — and use whichever unit the problem suggests.

Example. — Suppose the water above a mill dam to be 15 feet higher than the stream below; what is its pressure on a square foot whose middle point is at that depth?

In this case the cubic foot is a proper unit, and *the mass of a cubic foot of water is about* 62.4 pounds. The pressure on the square foot, being equal to $d \times a \times h$, is $62.4 \times 1 \times 15$; it is the weight of 936 pounds.

f. In many cases the area is not given. We speak of the pressure of the atmosphere, and the pressure of water in the sea, without specifying any area. In such cases a unit area is understood.

Examples. — 1. At a place where the ocean is 1000 feet deep, what is the pressure of the water at the bottom?

If the density of the sea water is .037 pound per cubic inch, the pressure at a depth of 1000 feet, represented by $d \times a \times h$, is $.037 \times 1 \times 12000 = 444$; it is the weight of 444 pounds on every square inch.

2. How much would the volume of a cubic inch of water be reduced if taken from the surface to the depth of 1000 feet? (§ 40, *b.*)

3. Is the density of sea water greater as we go downward?

g. Questions just like those in the examples above may be asked in regard to the pressure of the atmosphere. Air is a fluid, and we, with other terrestrial objects, are at the bottom of an ocean of it. What is the pressure of the atmosphere? We cannot compute it directly, as the pressure of water is computed; because,

1. The height, h, of the atmosphere is unknown.
2. The density, d, of the air is less and less from the earth upward. (Why? § 40, *b*.)

But it may be found indirectly by balancing it by a liquid which can be measured. Torricelli taught us how to do this.

h. Torricelli's experiment may be repeated as follows: Take a glass tube more than 30 inches long, fill it with mercury, and cover the open end firmly with the finger (Fig. 102, *a*). Then invert the tube, place the open end in a dish of mercury, and withdraw the finger. The mercury will sink but a little way in the tube (Fig. 102, *b*); it will stand about 30 inches above the level of the mercury in the dish. The space in the tube above the mercury is a vacuum; that is, it contains no air. It is known as a *Torricellian vacuum*.

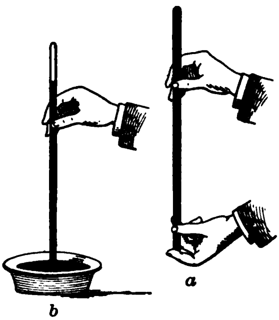


Fig. 102.

The mercury is upheld in the tube by the downward pressure of the atmosphere on the mercury in the dish. The mercury column and the atmosphere just balance each other.

i. We can compute the pressure of the mercury which balances the atmosphere, for we know its density, d, to be .49 pounds per cubic inch (13.56 g. per cubic centimeter) at 0° C., and can measure its height, h, which is found to be about 30 inches (76 cm.), if the experiment is made at the level of the sea. Hence the pressure of the mercury represented by

$d \times a \times h$, is $.49 \times 1 \times 30 = 14.7$; it is the weight of 14.7 pounds per square inch (1033.3 g. per square cm.). And this is the atmospheric pressure which balances the column of mercury 30 inches high.

75. **The Barometer.** — *a.* Any instrument by which changes in the pressure of the atmosphere can be detected and measured, is a *barometer*.

The simplest form of barometer is the Torricellian tube and cistern (Fig. 102, *b*). If the pressure of the atmosphere increases, the mercury is pressed up to greater height; if it decreases, the mercury sinks in the tube to a lower level. So the height of the mercury column represents the atmospheric pressure.

The tube and cistern are inclosed in a frame, for protection, and provided with a graduated scale to measure the height of the mercury column. And besides these parts, certain artifices are employed to secure accuracy in the measurement.

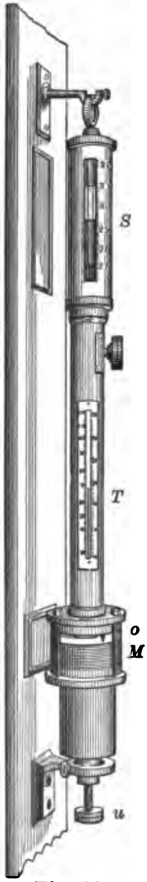


Fig. 103.

b. A "standard barometer" is represented in Fig. 103. The tube and cistern are encased in a metal frame, a portion of the mercury in the cistern being visible at *M*, and a few inches of the tube at the upper end. By means of the graduated scale and vernier at *S*, the height of the column can be read to within .002 of an inch.

But it is evident that if the mercury should rise in the tube, it would sink in the cistern, and that the fixed scale, *S*, would not then show the true height of the column above the surface in the cistern. This error is corrected by raising the surface of the mercury as much as it had fallen. The end

of a little ivory pointer at *o* shows where the surface should be, and in order to place it there, the bottom of the cistern is made of flexible materials and rests upon the upper end of the screw *u*, so that by turning the screw it may be lifted or lowered at pleasure. The cistern with a flexible bottom, and an ivory or bone pointer to mark the true place of the mercury surface, is known as *Fortin's cistern.* *T* represents a thermometer. Why should there be a thermometer (*f*)?

c. Observations show that the height of the column of mercury in the barometer is changing almost continually at every place, which proves that the atmospheric pressure is as constantly fluctuating. The height varies between about 28 and 31 inches. Hence the pressure varies between the weight of $\frac{28}{30}$ of 14.7 and $\frac{31}{30}$ of 14.7 pounds per square inch (§ 74, *i*). One can therefore compute the pressure of the atmosphere at any time or place from the barometric height.

It should be carefully remembered that *the barometric height represents the atmospheric pressure, and nothing else directly.*

d. Observations have shown that changes in the height of the barometer column are associated with changes in the weather. This fact makes the barometer a weather indicator. Not that any particular height of the mercury stands for any particular kind of weather, but the *motions* of the mercury suggest the *probabilities* of weather changes, because changes in weather accompany changes in atmospheric pressure.

A sudden and extreme fall of the mercury is an indication of an approaching wind storm. A gradual fall of the mercury indicates the approach of foul weather. A rise of the mercury indicates the approach of fair weather. But foul weather does not necessarily mean rainy weather, because moisture in the air does not directly affect the atmospheric pressure. The barometer is not a rain prophet.

e. The height of the barometric column depends on the altitude of the place. This is evident when we remember

that the pressure of a fluid varies with the depth of the place below its surface (§ 72). The "level of the sea" is the standard level; and the average height of the column at that level, 76 cm. (or 30 inches), is the standard barometric height. Above this level the mercury stands lower, and below it the height of the column is greater. But the pressure varies more rapidly than the altitude of the place (§ 74, *g*, 2).

f. The height of the barometric column is not due, altogether, to the pressure of the atmosphere; it depends a little on its temperature. Like most substances, mercury expands when warmed, and hence the height of the barometric column will vary with changes of temperature, even if the atmospheric pressure is not changed. But a column 76 cm. high at any given temperature, represents a perfectly definite pressure. The standard barometric height represents a pressure of 1033.3 g. per square centimeter (§ 74, *i*). A pressure equal to 1033.3 g. per square centimeter, or 14.7 pounds per square inch, is often called *an atmosphere.*

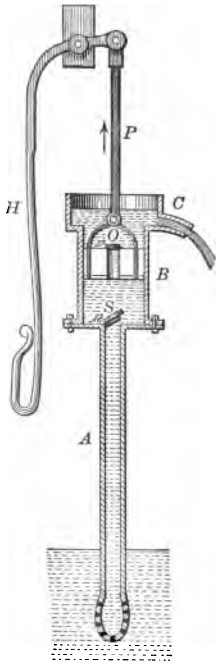


Fig. 104.

76. **The Common Pump.** — *a.* In this instrument the atmospheric pressure is made to lift water from wells and cisterns. It consists of a cylinder, *B* (Fig. 104), which opens below into a pipe, *A*, leading to a reservoir of water. A valve, *S*, closes the hole, and opens upward. A close-fitting, solid cylinder, called a piston, is lifted and lowered by a lever, *H*. There is a valve, *O*, in this piston, opening upward. By lifting and lowering the piston, the water is lifted to the spout, *C*.

b. When the piston is lifted, the air above it will be lifted out of the cylinder. The space which the air below the piston has to fill is enlarged, the air expands, and the pressure on the water below is lessened. Then the pressure of the atmosphere on the surface of the water outside, in the well or cistern, will push the water up the pipe *A*, through the valve *S*, into the cylinder *B*. When the piston is pushed down, the valve *S* will close and prevent the water from returning to the well. But the valve *O* will be opened, and the piston will be forced down through the water. When the piston is lifted again, the water above it will be lifted to the spout, while the atmospheric pressure will drive another cylinderful up through *S* into *B*. Does a pump "draw" the water up?

c. But there is a limit to the height to which the atmospheric pressure can lift water. We have seen that it can support a column of mercury (§ 74, *h*) about 30 inches high. Since mercury is, at ordinary temperatures, about 13.6 times heavier than an equal volume of water, the same pressure would support a column of water 30×13.6, or 408, inches high (34 feet). So, practically, the top of the lower cylinder *A* must be less than 34 feet above the water in the well. Of course the water may be lifted in cylinder *B* to an additional height equal to its length.

The total height to which water may be raised by the pump is limited only by the length of the pump and the amount of energy at command. The amount of energy required in any case, in foot-pounds (§ 17, *f*), would be found by multiplying the total mass of water in the pump by the distance from the water in the well to the spout.

77. **The Force Pump.** — *a.* Where water is to be raised to considerable height, or thrown in a stream to considerable distance, a *force pump* is used.

A model of the force pump is shown in Fig. 105. The piston has no valve. Near the bottom of the cylinder a side

tube leads into a closed air chamber, *K*. A tube, *T*, reaches from near the bottom of this chamber, through the top of it, air tight, and thence to the place where the water is to be delivered. A fire engine is a force pump. The hose is an extension of the tube *T*.

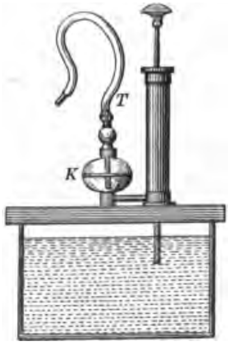


Fig. 105.

b. When the piston is raised, water is lifted through the pipe and valve into the cylinder by atmospheric pressure. When the solid piston is pushed down, the water is driven through a valve into the air chamber. When the water covers the lower end of the tube in *K*, no more air can get out of the chamber, and that which fills the dome is condensed more and more by each stroke of the piston. The reaction of this condensed air pushes the water out through the tube *T*. Without the air chamber the water would be lifted to the same height, if the side tube were directed upward, but it would issue in jets. The steady pressure of the condensed air causes the stream to be steady.

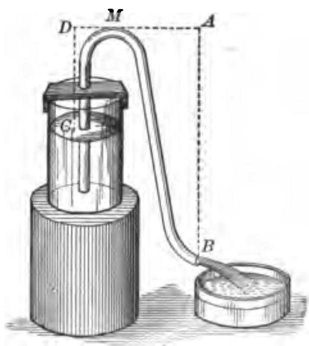


Fig. 106.

78. **The Siphon.** — *a*. The siphon is an instrument by which liquids may be transferred from one vessel to another at a lower level. It consists of a bent tube, one branch of which is longer than the other. Fig. 106 represents a siphon in operation.

To put the siphon in action, it is filled with the liquid, its ends closed, the shorter branch inserted in the liquid, and its ends opened. The liquid will then flow steadily until the end

of the shorter branch is uncovered, or until the level of the water is the same in the two vessels.

b. The flow of water is caused by the pressure of the atmosphere. In the siphon at *C* there is an upward pressure equal to the downward pressure of the atmosphere at that level (§ 71, *d*). There is also an upward pressure of the air on the water at the other end, *B*. These upward pressures of the atmosphere, at *B* and *C*, are practically equal, and since the atmosphere is able to support a column of water 34 feet high, the water, evidently, cannot flow out of either end of the siphon by its own weight alone.

But the weight of the water in the long arm is greater than that in the short arm, and balances more of the atmospheric pressure. So there is less unbalanced atmospheric pressure at *B* to push the water over toward *A* than there is at *A* to push it over toward *B*, and the water must flow in the direction of the greater pressure.

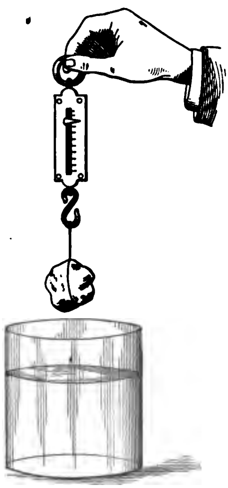


Fig. 107.

79. **Buoyancy.** — *a.* It is well known that a cork or a piece of wood, if placed under water and released, will rise to the surface, and that such substances as smoke, and such bodies as balloons, will rise in the atmosphere. Why is gravity unable to hold these bodies down?

Fluids oppose gravity even on such bodies as blocks of iron and stone. You can detect this opposition of water as follows:

Hang a piece of iron or marble upon a spring balance (Fig. 107), and note the downward pull of gravity while it is in the air. Lower the body into a vessel of water, and again note the reading of the scale. The pull of gravity now seems to be less than before. The water, in some

way, balances a part of the gravity of the body. This upward push against a body which is immersed in a fluid is called *buoyancy*.

Experiment 43. — *Object.* To find how much of the weight of the solid immersed in water is supported by the liquid.

Apparatus. A graduated cylinder. A balance and box of masses. A piece of metal or stone, slender enough to hang in the cylinder without touching the sides, and long enough to enable it to displace a quite large quantity of water.

Manipulation. Fill the cylinder to a convenient height with water, and carefully note the number of cubic centimeters.

Hang the solid from the hook of the balance by a fine thread; counterpoise it by masses from the box. Note its weight.

Lower the solid into the water in the cylinder; see that it does not touch the sides, and that no air bubbles remain clinging to it. Again counterpoise it by masses from the box. Note its weight while in the water. Note the volume of the water and solid together. The record may be written as follows:

Volume of water in the cylinder	—— cc.	*A*
Weight of the solid in the air = the weight of .	—— g.	*B*
Weight of the solid in the water = the weight of .	—— g.	*C*
Volume of both solid and water	—— cc.	*D*

Computations. $B - C$ is the weight of the solid which the water balances.

Note also $D - A$, which is the volume of the water displaced by the solid when immersed.

Experiment 44. — *Object.* To find the weight of the water which the solid used in the preceding experiment displaces when immersed.

Place a beaker on a balance pan, and counterpoise it with sand or shot. Measure into a beaker the $D - A$ cc., found in the last experiment, and counterpoise it by masses from the box. The weight of these masses equals the weight of the displaced water.

b. If the work of the last two experiments has been successfully done, you will see that *the weight which a solid appears to lose when immersed in water, equals the weight of the water which the solid displaces.*

This fact holds true in regard to all other fluids, and may be stated in a general form as follows:

When a body is immersed, wholly or partly, in a fluid, it is buoyed up by a pressure equal to the weight of the fluid which it displaces.

This relation between the weight of a body and that of the volume of fluid displaced, was discovered by Archimedes about two hundred and fifty years before the Christian era began. It is known as the *Principle of Archimedes.*

c. The explanation of buoyancy is as follows: Let *abcd* (Fig. 108) represent a section of a body immersed in a fluid. The downward pressure on the top is equal to the weight of a column of the fluid whose volume is represented by *abef.* The upward pressure on the bottom is equal to the weight of a column of the fluid whose volume is represented by *cdef* (§ 72). The buoyancy is the difference in these two pressures. It is equal to the weight of a column of the fluid whose volume is the difference in volume of these two columns. But this difference — *cdef* − *abef* = *abcd* — represents the volume of the body itself, and, of course, the volume of the fluid displaced.

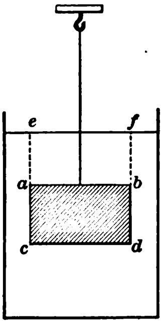


Fig. 108.

d. Three cases should be considered:

1. The weight of fluid displaced may be less than that of the body which displaces it. Then buoyancy is less than gravity, and the body sinks. Think of iron or stone in water.

2. The weight of the fluid displaced may be greater than that of the body which displaces it. Then buoyancy is greater than gravity, and the body rises. Think of wood in water, and a balloon in air.

3. The weight of the fluid displaced may be equal to that of the body which displaces it. Then the body will neither sink nor rise, but float in the fluid. Think of a cloud in the atmosphere. Fill a small bottle partly full of water; close

its mouth while you insert it in water, mouth down. By a few trials you can so adjust the quantity of water in the bottle that it will neither sink nor rise when immersed. Put an egg in fresh water; in strong salt water. Then mix the two gradually, till the egg will neither sink nor rise.

e. We have seen that the loss of weight, when a body is immersed in water, is equal to the weight of the body's own volume of water (*b*). We make use of this fact when we wish to find out how many times heavier a certain volume of one substance is than the same volume of another.

Experiment 45. — *Object.* To find the ratio of the weights of equal volumes of iron and water.

The manipulation and the form of the record are suggested by the notes of one experiment, as follows:

	Weight of the iron in air	= weight of 115.56 g.
	Weight of the iron in water	= weight of 100.08 g.
∴	Weight of an equal volume of water	= weight of 15.48 g.
	And the ratio of the weights of equal volumes of iron and water is 115.56 ÷ 15.48 . . .	= 7.46

f. Whatever may be the weight of a cubic centimeter, a cubic inch, or any other volume of water, at any temperature, the weight of an equal volume of iron, at the same temperature, is 7.46[1] times as great.

If the weight of a cubic foot of water is that of 62.4 pounds, then that of a cubic foot of iron is the weight of 465.5 pounds (62.4×7.46).

80. **Specific Gravity.** — *a.* The *specific gravity* of a substance is the ratio of its weight to that of an equal volume of some standard substance. Thus 7.46, as found by the last experiment, is the specific gravity of iron, water being the standard.

Water is the standard for all solids and liquids; air, or hydrogen, is the standard for gases. But, inasmuch as the volume of the same mass is changed by any change in tem-

[1] The true value is different for different kinds of iron, ranging from 7.2 to 7.79.

perature, it is necessary to have a standard temperature as well as a standard substance. The standard temperature is 4° C.

Remember that specific gravity is a *ratio;* it is merely a numerical quantity, and is the same whatever units may be employed.

The relative density (§ 6, *f*) and the specific gravity of a substance are expressed by the same number. But one refers to *mass,* while the other refers to *weight.*

Experiment 46. — *Object.* To find the specific gravity of glass.

Apparatus. The balance. A beaker, or other dish, for water. Fine silk thread by which to suspend the glass. A glass stopper without air bubbles or cavities within.

Manipulation. First, weigh the glass in the air in the usual way. Next, suspend the glass from the hook of the balance, and weigh it in water.

Precautions. See that the glass is completely immersed. See that it does not touch the dish. See that no air bubbles cling to it; if there be any, they must be removed. The feather end of a quill may be used to remove them.

Notes. A brief statement of the object and method as usual. Every value as soon as it is obtained. A skeleton form, like that below, prepared beforehand, is desirable, so that the numerical values can be inserted at once.

Weight of the glass in air	——
Weight of the glass in water	——
∴ Weight of an equal volume of water	——
∴ Specific gravity of glass —— ÷ —— . . .	——

b. The method employed in the above experiment may be used to obtain a close value of the specific gravity of any solid (not a powder) which is specifically heavier than water, and is insoluble in that liquid. But if the greatest possible accuracy is required, certain "corrections" must be made in the result. The true weight of a body is not found by weighing it in air, because the body is buoyed up by the weight of its own volume of air (§ 79, *b*). The weight in air should be corrected by adding the weight of an equal volume of air. Again: The

temperature of the water is not likely to be the standard 4° C. If it is higher than 4° C., the water is expanded, and the volume displaced will weigh less, and on this account the specific gravity of the solid will be found too large. This error can be made less by using ice water in the experiment.[1]

Experiment 47. — *Object.* To find the specific gravity of beeswax.

Apparatus. Balance. Dish for water. Fine thread for suspension. Wax. A sinker heavy enough to sink the wax in water. This sinker may be a piece of sheet lead with a slender wire nail driven through the center. The head can be bent to serve as a hook for suspension. The point may be thrust into the wax to fasten wax and sinker together.

The manipulation and record are suggested by the following form:

Weight of the wax alone in air	= ——	W
Weight of the sinker alone in water . . .	= ——	S
Weight of wax and sinker together in water	= ——	T

$$\text{Specific gravity}^{2} = \frac{W}{W + S - T} = \text{——}.$$

This method may be used for the specific gravity of any solid (not a powder) which is specifically lighter than water and insoluble in that liquid.

Experiment 48. — *Object.* To find the specific gravity of loaf sugar.

Since water dissolves sugar, we must use some other liquid which will not. If we find the specific gravity of sugar compared with this liquid, we can get the specific gravity compared with water by multiplying it by the specific gravity of the liquid. Turpentine may be used; its specific gravity is .87.

Apparatus. Balance. Beaker for turpentine. Thread. Turpentine.

Manipulation and record suggested by the following form:

Weight of the sugar in air	—— . . .	W
Weight of the sugar in turpentine	—— . . .	w
∴ Weight of an equal volume of turpentine . . .	—— . .	$W - w$

[1] Directions for making these and other corrections necessary for the greatest accuracy, may be found in Stewart and Gee's *Practical Physics*, Vol. I. Only advanced students should be asked to make them.

[2] The weight of the sinker in air cancels out as follows:

Write W for weight of wax in air; w for weight of sinker in air; S for weight of sinker in water; T for weight of both in water. Then,

$w - S$ = weight of water displaced by sinker;

$W + w - T$ = weight of water displaced by both;

$W + w - T - (w - S)$ or $W + S - T$ = weight of water displaced by wax;

∴ specific gravity $= W \div W + S - T$.

$$\therefore \text{ Sp. gr. of sugar compared with turpentine, } \frac{W}{W - w} = \text{——}$$

$$\therefore \text{ Sp. gr. of sugar compared with water, } \frac{W}{W - w} \times .87 = \text{——}$$

This method may be used for the specific gravity of any solid (not a powder) which is soluble in water.

Experiment 49. — *Object.* To find the specific gravity of turpentine by means of a specific gravity bottle.

A specific gravity bottle is a bottle made to hold a certain number of grams of water at a certain temperature. One holding 50 g. at 15° C. is a convenient size. It is provided with a ground glass stopper which fits its mouth with great nicety. In one kind there is a small hole through the stopper, and the bottle holds the specified mass of water when it is filled to the top of the stopper. In another kind the stopper is solid, and a mark on the neck shows the level to which the bottle must be filled. With such bottles one can readily obtain equal volumes of liquids.

Precautions. See that the bottle is clean. Never fill it with one fluid while it is wet with another. Even the small quantity that clings to the glass after rinsing and draining the bottle will contaminate the next liquid put into it. After washing and draining the bottle, rinse it out with a small quantity of the liquid to be used. Handle the bottle just as little as possible, since the warmth of the hand will enlarge it. Lift it by the neck, not by the body.

Manipulation. Find the weight of the clean, dry bottle. Place the bottle on a plate while you fill it completely with the water. Insert the stopper, and push it gently but firmly to its place. The excess of liquid will escape through the hole in the stopper, and the last tiny air bubble should escape with it, leaving the bottle full to the top of the stopper. Wipe the outside of the bottle. Find the weight of the bottle and water, and in the same way, of the bottle and turpentine.

The record and computations are suggested by the following form:

	Weight of the bottle when empty	—— . . .	W
	Weight of the bottle filled with water	—— . . .	A
∴	Weight of the water held by the bottle at —— ° C.	—— . . .	w
	Weight of the bottle filled with turpentine . . .	—— . . .	W'
∴	Weight of the turpentine alone . . . $W' - W =$ ——		

$$\text{Sp. gr.} = \frac{\text{weight of turpentine}}{\text{weight of water}} = \frac{W' - W}{w} = \text{——}$$

By this method the specific gravity of any liquid may be found. For volatile liquids, such as alcohol and ether, a bottle with a solid stopper is to be preferred.

Experiment 50. — *Object.* To find the specific gravity of a liquid by its buoyancy on a solid.

We have seen (§ 79, *b*) that the apparent loss of weight experienced by a solid immersed in any liquid is the weight of an equal volume of the liquid. Hence we can find the weights of equal volumes of two liquids by finding the apparent losses of weight of the same solid when immersed in them.

Apparatus. Balance. Two beakers. Glass stopper. Turpentine or other liquid. Fine thread.

Manipulation. Suspend the glass stopper by fine thread from the hook of the balance, and counterpoise it with box-masses. Then immerse it in turpentine, remove air bubbles, and again counterpoise it. Wipe the turpentine off the stopper completely. Immerse the stopper in water, and counterpoise it again.

The record and computations are suggested by the following form:

Weight of the glass stopper in air . . . . . —— . . . W
Weight of the glass stopper in turpentine . . —— . . . W'
Weight of the glass stopper in water . . . . —— . . . w
∴ Weight of turpentine equal in volume to the stopper $= W - W'$ ——
∴ Weight of water equal in volume to the stopper, $W - w =$ ——

$$\therefore \text{ Sp. gr. of turpentine} = \frac{W - W'}{W - w} = \text{——}$$

Experiment 51. — *Object.* To find the specific gravity of a liquid by means of a hydrometer.

A hydrometer consists of a glass tube, with one or two bulbs at the lower end containing enough air to make the whole instrument specifically lighter than water, and at the same time some heavy substance, as mercury or shot, enough to make the instrument stand upright when in a liquid (Fig. 109). The tube above the bulb is graduated.

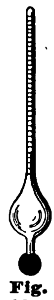


Fig. 109.

The Principle. Any body specifically lighter than a liquid, will sink in that liquid just far enough to displace a volume whose weight is equal to its own. This follows from the principle of Archimedes (§ 79, *b*). Any such body will sink deeper in a lighter liquid, and displace more. Hence:

The volumes of different liquids displaced by a hydrometer are inversely as the specific gravities of the liquids. The specific gravity of a liquid is indicated by the depth to which the instrument sinks.

The numbers on the stem, in some kinds of hydrometer, are specific gravities, while in other kinds they are simply arbitrary numbers called *degrees*. In the latter case a table of specific gravities is needed to show the values of the scale readings.

Apparatus. A tall, narrow jar. A pair of Beaumé's hydrometers.[1] Liquids.

Manipulation. Insert the clean, dry hydrometer in the liquid whose specific gravity is to be found. See that no air bubbles remain upon it, and that it does not touch the sides of the jar. Place the eye on a level with the surface of the liquid in the jar, and note the scale reading. Do not be misled by the capillary rise of the liquid on the glass (§ 49, *a*). Consult a table of specific gravities for that which corresponds to this reading.

81. **Studies.** — 1. A narrow tube open at both ends may be filled with water by immersion. If one end be then closed with the finger, the tube may be held in the air with its open end downward, without losing the water. Try it, and explain why the water does not fall out.

Try also a wide-mouth bottle, and explain why, in this case, the water will fall out.

2. A wide-mouth bottle full of water may be held bottom up without spilling the water if a card is gently pressed against its mouth while it is being inverted. Try it, and explain why the water does not fall out.

3. A jar (*A*, Fig. 110), having been partly filled with water by immersion, is lifted, mouth downward, and placed upon a shelf in the cistern; the water does not fall out. By what force is the weight of the water *LC* supported? Where is this force exerted on the water, and how comes it to be an upward pressure to balance the weight of the water in the jar?

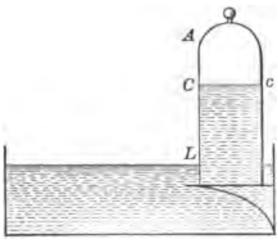


Fig. 110.

4. If the barometric height is 75 cm. when the experiment is made, find the upward pressure per square cm. which supports the water (*LC*, Fig. 110).

5. If *C* is 30 cm. above the level of the water in the cistern, compute the downward pressure per square cm. of the water in the jar. And next compute the upward pressure per square cm. against the air in the jar, the barometric height being 75 cm.

6. A pipe supplies water to the upper rooms of a 3-story building, terminating at a height of 36 feet above the lower floor. What pressure per square inch must the pipe at the floor sustain?

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[1] One is for liquids, like ether, lighter than water; its zero is at the lower end of the stem. The other is for liquids heavier than water; its scale begins with 10, the upper end of the stem. The beginning of the scale in both cases is the mark for the level of water.

COMPRESSIBILITY AND EXPANSIBILITY OF GASES.

82. **Comparison of Liquids and Gases.** — We have seen that air is reduced .5 of its volume by the pressure of one atmosphere per square inch, while water is reduced by an equal pressure only .00005 of its volume (§ 40, *b*). On the other hand the volume of a given mass of air increases indefinitely as the pressure upon it is reduced toward zero, while the volume of a given mass of water, under the same condition, is apparently unchanged. As with water and air, so with other liquids and gases.

Compressibility and expansibility are distinguishing properties of gases.

83. **Liquefaction of Gases.** — There is a limit to the compressibility of gases. The limit is reached when the gas becomes a liquid. Many gases are reduced to liquids by great pressure alone. Others require a low temperature, as well as great pressure, to liquefy them. But every gas becomes a liquid under some degree of pressure and cold combined. For example: Carbon dioxide is liquefied by a pressure of 53 atmospheres at ordinary temperatures; hydrogen, by a pressure of 300 atmospheres at $-29°$ C.

84. **The Law of Compressibility of Gases.** — *a.* The law that connects the volume of a given mass of any gas with the pressure exerted on it is known as *Boyle's law.* It was discovered by Robert Boyle, in 1662, and is stated as follows:

The volume of a given mass of air, if the temperature is not changed, varies inversely as the pressure upon it.

Experiment 52. — *Object.* To study the changes produced in the volume of a given mass of air by changes in the pressure to which it is subjected.

Apparatus. In Fig. 111, *A* and *P* are two glass tubes, of uniform bore, joined by a rubber tube, *RR*, and supported by a wooden stand.[1]

[1] The support consists of an upright board, *S*, of ¾-inch stuff, 4½ inches wide, and 42 inches long, fastened with strong screws to the edge of a block made

A contains the air to be measured. *P* and *RR* contain mercury, by which the required changes in pressure are obtained. *M* is a meter bar, by which the lengths of the air and mercury columns may be measured. *A* is fixed, but *P* may be lifted or lowered alongside of *M*, by means of a cord, as shown.

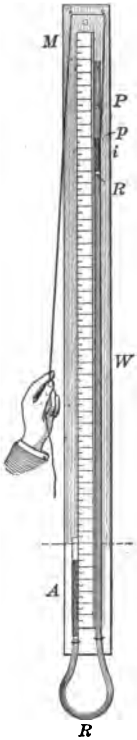

Fig. 111.

Explanations. If *P* is lowered until the mercury is at the same level in *A* and *P*, the imprisoned air in *A* receives the atmospheric pressure (§ 71, *d*). If the pressure tube is lifted so that the mercury level in *P* is carried up to *p*, then the air in *A* receives the pressure of the atmosphere and the *additional* pressure of the column of mercury reaching from the level of *A* to that of *p*. Hence one can change the pressure on the given mass of air in *A* by lifting or lowering the pressure tube, *P*.

Manipulation. Place the instrument on one corner of the table, and fasten it firmly by means of a clamp. The tube, *RR*, should hang down in front of the edge of the table. Read the barometric height, *H*. Place the mercury surfaces in the tubes *A* and *P* on the same level, and read the length of the air column in *A* which represents the volume, *V*, of the imprisoned air. Move *P* upward about 5 cm. Again read the volume, *V*, of air, and the difference in heights of the mercury in *A* and *P*. Call this *h*. Continue to lift *P*, and take readings of *V* and *h* up to near the top of the scale.

To use pressures less than the atmosphere: Lower the meter bar until its top is level with the surface of mercury in *A* and *P* when they are at the same height, by moving its screw. Then *lower P*, and again take readings of the volume, *V*, and the difference in heights of the mercury in *A* and *P*.

Remember that if the mercury in *P* is *below* the mercury in *A*, the value of *Ap*, or *h*, is negative. Why?

The record should be made of each reading, at the moment it is taken, in tabular form as follows:

Barometric height, *H*, = ... —— cm.

---

of 1-inch stuff, 12 inches by 4½ inches, which projects backward. Or *S* without the block may be hung against the wall of the room, on a nail which slips through a hole near the upper end. The meter bar may be fastened against the face of the board by a single screw at the upper end.

Volume of the Air, V	Difference in Heights in A and P, h	Total Pressure on the Air, $H \pm h$	Pressure × Volume.
.... c.c.	.... cm.	.... cm.	....
.... "	.... "	.... "	....
.... "	.... "	.... "	....

Having *observed* the values of V and h, *compute* the pressure, $H + h$, if the mercury in P is higher than in A, or $H - h$ if the mercury in P is lower than in A. And then, to compare the volumes and pressures, find the product of the two in each case, entering it in the table. Consider whether the products are all so nearly equal that their variations may be fairly attributed to the necessary errors or imperfections in the experiment. If they are so we may infer that the volumes of a mass of air, if its temperature is unchanged, vary inversely as the pressures. This inference follows because whenever *two products are equal, the factors are inversely proportional.*

Thus if $P \times V = P' \times V'$,
then $V : V' :: P' : P$.

b. More exact and more exhaustive experiments have been made since those of Boyle, which have shown that this law is not strictly true. There is a little difference in the compressibility of different gases, under pressures very great or very small, and that of any one gas varies when the gas is near the point of liquefaction.

c. As the volume of a given mass of air is less under greater pressure, its density must be greater. That is to say, *the density of a given mass of air must vary directly as the pressure upon it.*

d. Any so-called "empty" vessel is full of air. The volume of the air in the vessel is, if we neglect changes in temperature, always the same; but the mass of the air within depends on the atmospheric pressure. What if we could take off the pressure of the atmosphere? The air within would expand; a part would leave the vessel. The residue would fill the vessel, but there would be less of it. In other words, air may be

removed from vessels by reducing the pressure which holds it in. An instrument for removing air from vessels is called an *air pump.*

85. **The Piston Air Pump.** — *a.* The essential parts of this air pump are as follows:

A metal cylinder, *C* (Fig. 112), with a tube from the bottom, the other end of which passes through a metal plate, *p*. A piston, *P*, which fits inside the cylinder air tight, but is capable of moving from end to end. Valves *v* and *v'*, covering openings, one in the piston, the other in the tube, which can easily be lifted by pressure from below, but which are closed, all the more tightly, by pressure from above. The plate, *p*, is ground true, so that a glass vessel, *R*, whose mouth is also ground true, will fit it so closely that no air can pass between them. Compare this arrangement of valves with that in the common pump (Fig. 104). Think also why the valves of the air-pump must be lighter and fit more closely.

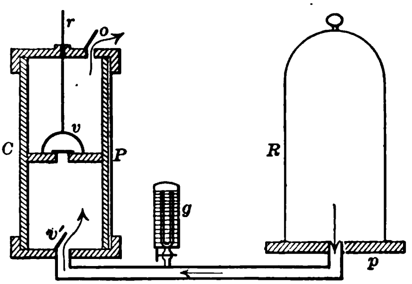

Fig. 112.

b. When *P* is lifted, the air pressure above it shuts the valve *v*, and the air is compressed between *v* and *o*, so that it closes the one and forces its way out through the other. The piston thus removes the air pressure from *v'*. Then the air in *R* expands, lifts *v'*, and fills the space below *P*, so that, when *P* has reached the top, the cylinder is full of air that has come out of *R*. When *P* is pushed down, the outside air closes *o*. The air below *P* closes *v'*, opens *v*, and the piston passes through the air. In this way every upward stroke takes a part of the remaining air out of *R*.

c. The removal of all the air by this means is not possible.

Only *a part* of the residue, after each stroke, can be taken out by the next. Why?

Practically, the exhaustion by the pump is limited by two causes: First, *leakage* — air finds a way between the joints even in the best-made instrument; second, *the weight of* v' — there must be air enough left behind to lift it. In the best modern pumps the second cause is removed by making the piston move this valve.[1]

d. The degree of exhaustion is measured by a mercury gauge (Fig. 113; Fig. 112, *g*). It consists of a U-tube inclosed in an air-tight tube, with a stopcock, by which it is attached to the pump. The closed limb of the U is full of mercury so long as the air presses in the open limb. But the pump removes this air pressure until it can no longer support the mercury, and then the residue of air pressure is measured by the difference of level in the two limbs. For example: Suppose the mercury is one fourth of an inch higher in the closed limb than in the other; then if the barometric height is 30 inches (§ 75, *c*), since $30 \div \frac{1}{4}$ is 120, the residue of air in the gauge and in the receiver is $\frac{1}{120}$ of the original mass.

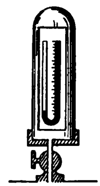

Fig. 113.

Example. — Suppose the difference of level in the gauge is .5 cm., and the barometric height 74.5 cm.; what degree of vacuum has been obtained? A good piston pump may reduce the air to $\frac{1}{300}$, or to .3 of one per cent.

86. **The Geissler Mercury Pump.** — *a.* The essential parts of this pump are as follows: A reservoir, *A* (Fig. 114), with one tube, *T*, more than 30 inches long, and another, *C*, also over 30 inches long, with its lower open end in a vessel of mercury. A reservoir, *B*, somewhat larger than *A*, joined by strong rub-

[1] Numerous interesting and instructive experiments with the air pump and apparatus, usually found in school cabinets, are described in text-books, which are easily accessible, and may be used as the teacher judges best.

ber tubing to the lower end of *T*. A bent tube, *OV*, provided with a side tube having a valve at *p*, by which communication may be made between the tube *T* and a vessel to be exhausted, *R*. There is another valve at *O* which closes the tube while the exhaustion is going on. The reservoir *B* is filled with mercury.

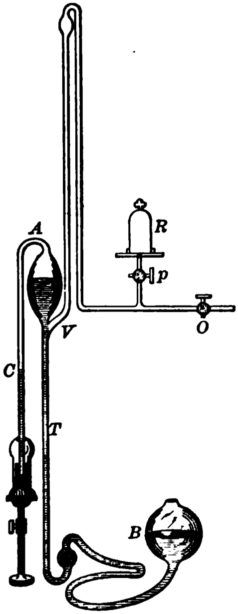

Fig. 114.

b. Let *O* be closed and *p* be opened. Then let *B* be lifted to the level of *A*; mercury from *B* will soon fill *A*, and overflowing, fill *C* also, while the bend in *OV* prevents its flow over to *R*. Let *B* be lowered. The mercury will sink out of *A* to a point below *V*, about 30 inches above *B*, and at the same time rise about 30 inches in *C*. A Torricellian vacuum (§ 74, *h*) is thus formed in *A*, and the air in *R* expands into it. *B* is again lifted; the mercury closes *V*, fills *A*, and drives the air out at the lower end of *C*. Thus one reservoirful of air has been taken from *R* and expelled into the open air. The lowering and lifting of *B* is repeated, and a part of the residue of air in *R* is, each time, removed. The vacuum in *R* is thus increased until it is little less than the Torricellian vacuum itself.

The Geissler pump is used to exhaust the globes of incandescent electric lamps, and for other purposes where high vacua are desired. It shares these uses, however, with another form of mercury pump, — the Sprengel pump, — by which the highest vacua, obtained by mechanical means, have been produced.[1]

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[1] *Physics, Advanced Course*, by George F. Barker. *The Physical Properties of Matter*, by Arthur L. Kimball.

DIFFUSION OF FLUIDS.

87. **The Intermingling of Fluids.** — *a.* Water will float on a solution of copper sulphate for the same reason that wood will float on water; its specific gravity (§ 80, *a*) is less. When a lighter liquid is above a heavier one, we should expect gravity to keep them unmixed for any length of time, if they are not disturbed. But this inference is not true to the facts. To see what actually happens when two liquids are placed in contact, we may proceed as follows:

Experiment 53. — Two liquids of different specific gravities may be brought together without mixing, by means of a siphon (§ 78, *a*).

B (Fig. 115) represents a beaker containing water. *A* represents a beaker containing strong solution of copper sulphate. *S* represents a siphon, by which the copper sulphate is to be transferred to the bottom of *B*. This siphon consists of two glass tubes connected by a rubber tube.

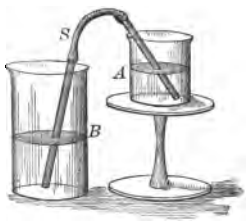

Fig. 115.

Fill the siphon[1] with copper sulphate by placing the end of the shorter glass tube in that liquid, applying the lips to the end of the longer, and slowly sucking the air out until the sulphate has risen in the tube nearly to the lips. *Stop before the sulphate reaches the mouth.* Pinch the rubber tube to close it tightly, while you put *A* upon its support and the end of the longer tube down upon the bottom of *B*. Open the rubber tube, and watch the lifting of the lighter, colorless liquid by the heavier blue one which the siphon carries over. To stop the siphon, pinch the rubber tube tightly, and lift it out of *B*. With a little care in these operations, the two liquids will not be mixed, but the plane of separation will be distinct. Cover the jar which contains the liquids with a plate, and leave it undisturbed for twenty-four hours or longer. If the blue tint appears to be spreading upward, the liquids must be slowly intermingling.

b. Strong brine may be put beneath water which is colored with litmus to make their plane of contact visible. In time

[1] Before trying to fill the siphon with the sulphate, practice with water until you can do it readily without drawing the liquid into the mouth or leaving much air in the end of the tube.

the lighter water will be found to have worked its way down into the brine a little, and the brine must have worked its way up a little at the same time, since the jar is just as full as at first. Alcohol is lighter than water, but if put on top of water, the two will gradually intermingle.

c. That gases behave in much the same way, may be observed as follows:

Select two half-pint, wide-mouth bottles, *H* and *A* (Fig. 116), whose mouths will fit smoothly together. Smear the mouth of *A* with tallow. Fill *H* with hydrogen gas (or coal gas, if this is more convenient) by holding it mouth down over a tube connected with a gas supply, which reaches up inside to the bottom. The gas, being lighter than air, will collect above, and drive the air out of the bottle. Then press the mouth of *H* down upon that of *A*, and leave them standing, say fifteen minutes. Finally, lift *H* from *A*, and bring a match flame to the mouth of each.

If the gases have intermingled, an explosion (harmless) will declare the fact.

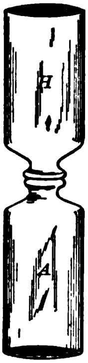

Fig. 116.

d. The intermingling of two fluids when placed in contact is called *diffusion*.

Liquids which will remain mixed when shaken together will diffuse when placed in contact; but those which, like oil and water, separate again on standing, will not diffuse. No such difference exists among gases. Every gas will diffuse into every other.

e. Since diffusion takes place when the lighter fluid is on top of the heavier, it cannot be due to gravity. It is believed to be due to molecular motion (§ 33). If the molecules of a liquid are in motion, they must be constantly jostling one another, so that the progress of any one in any particular direction is very greatly hindered, but not altogether stopped. We may conceive them to be dodging about from place to place among themselves. Accordingly, when two liquids are in contact, we can conceive the molecules of each to be wandering off among those of the other. This explains diffusion.

f. In gases the molecules are further apart than in liquids, and they must hinder one another much less on this account. Each can fly in a straight line until it collides with another, and their directions are changed only by such collisions. Hence their wandering ought to be less checked than that of the molecules of liquids. So that, where two gases are in contact, we can conceive the molecules of each as making rapid progress off among those of the other. This explains the fact that the diffusion of gases is more rapid than that of liquids.

88. **Osmose of Fluids.** — *a.* If two liquids are separated by a porous membrane or partition, one or both will pass through, so that a mixture of the two will be found on one or both sides.

Experiment 54. — Select a small funnel with a long stem. Wet a piece of parchment paper and bind it over the mouth of the funnel with a wide rubber band; the joint must not leak. Fill the funnel with strong solution of copper sulphate to a point on the stem, and support it in water (Fig. 117) with the liquids at the same level on the inside and outside. Watch the experiment for some time. If the water in the beaker becomes tinted with blue, the copper sulphate must be diffusing out. If the liquid rises in the stem, the water must be diffusing in faster than the sulphate is going out.

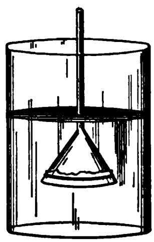

Fig. 117.

The intermingling of fluids through porous partitions is called *osmose.* The action in the porous partition is very much like capillarity (§ 40, *b*, *e*), but it is not the same. The conditions on which it depends are more numerous and complicated.

b. Substances which do not crystallize (§ 50, *a*), such as gum, starch, and gelatine, mix through porous membranes with extreme slowness, while those which can be crystallized, will, if dissolved in water, pass through very freely. These two classes of substances are called respectively *colloids* and *crystalloids.*

c. So great is the difference between colloids and crystalloids, that if the two are mixed they may be separated by osmose. For example: If arsenic or strychnine is mixed with ordinary articles of food, the mixture may be put into a glass vessel having a bottom of parchment paper, and suspended in water. The poison will diffuse out into the water, where it may easily be detected by chemical means, while the organic matter is left behind. This process of separating substances by osmose is called *dialysis.*

d. It has been found that if water and alcohol are separated by a caoutchouc membrane, the alcohol will pass through, but the water will not, so that a mixture is formed only on one side. This case illustrates a general fact in osmose. A membrane transmits the liquid which wets it. If the membrane is wetted by both liquids, it transmits both and more of that one which wets it in the higher degree.

e. The fluids in animal and vegetable bodies are separated chiefly by porous membranes or tissues, and are continually subject to the laws of osmose. Osmose is a most important action in all organic bodies.

VII. MOLECULAR ENERGY — HEAT.

HEAT A FORM OF ENERGY.

89. **Meaning of the Word Heat.** — *a.* The word *heat* is used in physics to denote the cause of the sensation of warmth.

But the sensation of warmth is produced in two very different ways, as, in one case, when we put our hands into warm water, and in another case, when we stand in the warm sunshine. In the one case the source of the heat — the water — is in contact with the hand; in the other case, the source of the heat — the sun — is distant. The action of the water is direct; the action of the sun is through the ether (§ 20, *c*).

b. The heat that is transmitted by the ether is called *radiant heat.* It is, in its nature, the same as light, and will be studied with light in a future chapter. At present we are to study heat considered as *that which enables matter to produce the sensation of warmth or cold by direct contact with the sense of touch.* In what follows let this distinction be carefully borne in mind.

90. **Heat is Energy.** — *a.* Energy (§ 17, *a*) has three characteristics:

1. It may be transferred from one body to another.
2. It may be transformed from one variety into another.
3. It suffers neither loss nor gain in these changes.

If it can be shown that heat has these characteristics, then heat is energy.

Experiment 55. — *Object.* To show that heat may be *transferred* from water to metal.

When one body warms another, does it really part with anything which the other receives?

A small beaker with warm water, a mass of metal which will slip into it, and a thermometer, will furnish an answer to this question. Proceed as follows:

Put the beaker into a wooden box, and pack it about with cotton wool.[1] Tie a thread to the metal. Put hot water into the beaker, and note its temperature as shown by a thermometer. Touch the metal, and notice that it feels cold, and then insert it into the water. After two or three minutes remove it, and find that it feels warm. Insert the thermometer, and find that the water is colder than before. The experiment shows that while the water lost heat, the metal gained it.

Experiment 56. — *Object.* To show that heat may be transformed into potential mechanical energy.

Set up the apparatus shown by Fig. 118. A flask, *f*, containing colored water. A bent tube, *t*, reaching from below the surface of the water through the air-tight stopper of the flask up and over into an empty beaker, *b*. Proceed as follows:

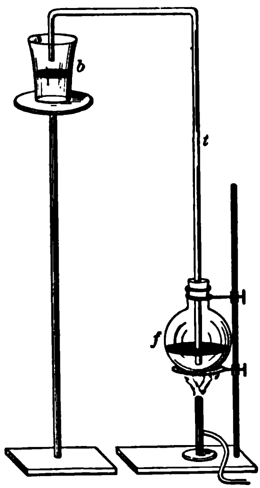

Fig. 118.

Find the mass of the empty beaker. Apply heat to the flask, and continue it until the beaker is partly filled with water. The work (§ 14, *a*) of lifting this water from *f* to *b* has been done by the heat from the flame. The energy expended in lifting the mass of water has become the potential energy (§ 17, *e*) of the water at *b*. Thus the heat has been transformed into potential mechanical energy.

b. The exact quantity of energy transformed cannot be found in this case, because the experiment has not been made with sufficient care to guard against losses. But you can make an estimate. Thus: Find the height of the water in *b* above the level in *f*; suppose it to be 2 feet. Find the mass of the water in *b*; suppose it to be .6 of a pound. Then (§ 14, *c*) the energy expended by the flame to lift the water was,

$$.6 \times 2 = 1.2 \text{ foot-pounds.}$$

[1] If heat passes out of the water, this jacket will help to keep it from getting away through the glass, so that it must go into the metal if anywhere.

This 1.2 foot-pounds of potential mechanical energy in the water at *b* was previously in the flame as heat.

c. Is there any loss or gain in the changes? This question was answered by experiments made by Joule during the seven years ending in 1850.

In one set of experiments Joule fixed a set of paddles to a vertical shaft, and put them into a brass cylinder containing water. A cord was wound around the upper part of the shaft, then extended sideways over a pulley, and fastened to a heavy mass which was allowed to fall. The energy of the falling mass was spent in stirring the water by rotating the paddles. The water was warmed by the friction between it and the paddles. In this way the mechanical energy of the mass was changed into heat in the water.

Now the quantity of heat required to raise the temperature of a pound of water 1° F. is always the same (§ 92, *b*). So Joule found the *quantity of heat produced* in the water, by multiplying the mass of the water in pounds by the change in its temperature in degrees. He found the *quantity of mechanical energy expended*, by multiplying the falling mass, in pounds, by the height through which it fell. His result was this: 772 *foot-pounds of energy, if converted into heat, will raise the temperature of a pound of water* 1° *F.* Thus Joule's experiments proved that heat and mechanical energy are mutually convertible in definite quantities.

d. More recent experiments have shown that Joule's number is too small. It varies with latitude and with temperature, but Rowland has shown that 777[1] is a good approximate value if we do not take these variations into account. When all losses are accounted for, 777 foot-pounds of mechanical energy is the equivalent of the heat which raises the temperature of 1 pound of water 1° F.

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[1] 780 for Manchester, where Joule's experiments were made, and at 10° C. See Everett's *C. G. S. System of Units* (1891).

Or, if we use the C. G. S. units, the heat required to raise the temperature of 1 g. of water 1° C. is equivalent to about forty-two million ergs of mechanical energy. This numerical relation is called the *mechanical equivalent of heat.*

e. If a piece of lead is placed on a block of iron, a few blows with a hammer will make it sensibly warm. Try it. The mechanical energy of the hammer is transformed into heat in the lead. It is done in this way. The molecules of the lead (§ 31, *e*) tremble under the blows, and the energy lost by the hammer when its motion is arrested, is transferred to the molecules of the lead. They were in motion before (§ 33), but their speed is increased by the blows, and the energy of the molecules in motion is heat.

That heat, as we have defined it (§ 89, *b*), is molecular energy seems to be proved by all experiments, notably by those of Davy, Rumford, and Joule.[1] Whenever the molecular agitation of a body is increased, the body is warmed; when it is diminished, the body is cooled.

MEASUREMENT OF TEMPERATURE AND HEAT.

91. **Temperature.** — *a.* If two bodies are placed in contact, one warm, the other cold, the warm body will impart molecular energy, that is heat, to the cold body until both are equally warm. The body which gives heat to the other is said to have a higher temperature; that which receives heat, is said to have a lower temperature. If no heat is transferred from either of two bodies to the other, they are said to have the same temperature. Temperature may be defined in two ways:

As a fact: Temperature is the condition of a body which determines whether it shall give heat to, or receive heat from, others.

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[1] See Tyndall's *Heat Considered as a Mode of Motion*, for descriptions of these experiments.

As a theory: Temperature is the relative kinetic energy (§ 17, *d*) of the molecules of bodies.

b. The sense of touch will not always correctly tell us whether two bodies have equal temperatures. For example: Wrap a piece of metal in a piece of flannel; after a little time they will have equal temperatures. But if then you touch them both, the metal will feel colder than the flannel. Try it. The sensation of cold depends partly on the rate at which heat is transferred from the hand, and the metal takes it away faster than the flannel.

c. How, then, can we compare the temperatures of two bodies? It can be done only by comparing the changes which occur in producing their temperatures. Changes in volume are more nearly proportional to the changes in temperature than any others produced by heat, and hence *temperatures are compared by measuring the changes in volume which accompany them.*

Experiment 57. — *Object.* To study the changes in volume that accompany changes in the temperature of a given mass of air, the pressure upon it remaining constant.

In the stem of the bulb-tube *bt* (Fig. 119) is a short thread of mercury, *m*, by which a certain mass of air in the bulb and stem is shut off from the air outside. The bulb may be about an inch in diameter, the stem about $\frac{1}{8}$ of an inch in diameter, and 12 inches long.

Fig. 119.

To get *m* into place, warm *b*, then insert the open end of *t* in mercury. The mercury will soon enter the end of *t*, and when about $\frac{1}{4}$ of an inch has entered, lift the tube out and let the bulb cool; *m* will go on toward *b*. By trial it may be made to stand near *b*, as shown, when the bulb is as cold as the air of the room.

Support the bulb-tube vertically by the clamp of a retort stand at the upper end. Then consider these questions: Is there a constant mass of air confined in the bulb-tube? What is the pressure upon it? Will the pressure be constant during the experiment?

Mark the stem at the bottom of *m*, and put the bulb into a beaker of water. If the water has the temperature of the air, *m* will not move. But if it move, mark its place on the stem. Take the temperature of

the water by inserting a thermometer. Pour a little hot water into the beaker and mix it thoroughly so as to warm the water a little. The air within will soon take the temperature of the water; the air in the stem will lengthen to a certain point and stop. Mark the place of *m*. Add a little more hot water to raise the temperature; notice the lengthening of the air column, and mark the place of *m* when it stops. Repeat, raising the temperature little by little until *m* is near the top of *t*. Finally ascertain whether the lengthening of the air column has just kept pace with the increase in the temperature of the water in the beaker, by measuring the several distances between the marks on the stem, and comparing them with the changes noted in the temperature.

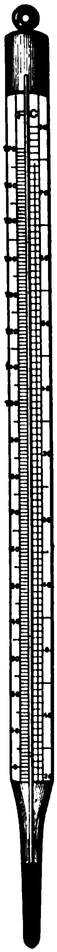

Fig. 120.

d. In the case of air *the change in temperature is proportional to the change in volume that goes on with it*. This is true of all gases, and very nearly true of some other substances. If we can measure the expansion or the contraction which takes place in such a substance, we can find values to represent the changes of temperature which occur at the same time. This principle is embodied in *Thermometers*, instruments for comparing the temperatures of bodies and measuring their changes.

Mercury is a liquid metal whose expansion by heat is remarkably uniform, and neither too great nor too small for practical purposes. It is the substance used in most thermometers.

e. The mercurial thermometer (Fig. 120) consists of a glass tube of fine bore with a bulb at one end. The bulb and a part of the stem are full of mercury. The space in the tube above the mercury is a vacuum, and the end of the tube is hermetically sealed. A scale to measure the expansion and contraction of the thread of mercury is attached to the stem, or, in the better instruments, engraved on the stem itself.

The scale must be made separately for each instrument, because the bulbs of different instruments are not

the same size, and the bores of their tubes not equally fine, so that their mercury threads do not lengthen equally for the same change in temperature.

f. In graduating the scale, two "fixed points" are first found and marked. These fixed points represent two "standard temperatures," one being the temperature at which ice melts, the other being the temperature at which water boils under an atmospheric pressure of 76 cm. (§ 75, *f*). These two temperatures are invariable.

The lower "fixed point" is found as follows: The bulb and lower part of the stem is packed in melting ice from which the water drains away freely. The mercury thread shortens for a time, then stops. The top of it is then marked on the stem or scale.

The higher "fixed point" is found as follows: The bulb *and stem* are immersed in the steam just above the surface of boiling water. The mercury thread will lengthen for a time and then stop. The top of the thread is then marked on the stem or scale.[1]

Finally, the distance between the fixed points is divided into a certain number of equal parts, and the divisions are extended above and below them along the stem. These divisions are called *degrees.*

g. There are three ways of numbering the degrees:

1. The melting point of ice is marked 0; the boiling point of water is marked 100, and there are 100 divisions between. In this case the instrument is called a *Centigrade thermometer,* and represented by C.

2. The melting point of ice is marked 32; the boiling point of water is marked 212, and there are 180 divisions between.

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[1] The pressure of the atmosphere not being the standard 76 cm., nor the temperature the standard 0° C., while the experiment is going on, the length of the thread is "corrected," and it is the place where the top would be under those conditions, that is marked on the scale.

In this case the instrument is called a *Fahrenheit thermometer*, and represented by F.

3. The melting point of ice is marked 0; the boiling point of water is marked 80, and there are 80 divisions between. In this case the instrument is called a *Reaumur thermometer*, and represented by R.

h. In Fig. 121 these three scales are shown side by side for comparison. Observe that the same temperature has a different value on each scale. Observe again:

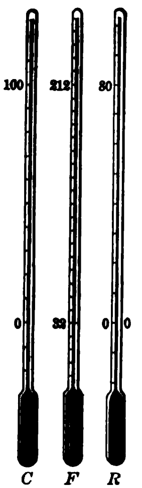

Fig. 121.

$$100° \text{ C.} = 180° \text{ F};$$
$$\therefore\ 5° \text{ C.} = 9° \text{ F.}$$

Hence, to convert *degrees* Centigrade to *degrees* Fahrenheit, multiply the C.° by $\frac{9}{5}$. Thus 50° C. are equal to $50 \times \frac{9}{5}$, or 90° F. Observe again that the

$$\text{temperature } 100° \text{ C.}$$
$$= \text{temperature } 180° \text{ F.} + 32°.$$

Hence to convert *temperatures* Centigrade into *temperatures* Fahrenheit, multiply the C.° by $\frac{9}{5}$ and add 32. For example: If the temperature of a room is 20° C., what is its temperature according to Fahrenheit?

$$20 \times \tfrac{9}{5} + 32 = 68. \quad \text{It is } 68° \text{ F.}$$

To convert Fahrenheit temperatures to Centigrade temperatures: First subtract 32, and then multiply by $\frac{5}{9}$. For example: On a hot day in summer the temperature according to a Fahrenheit thermometer was 92°; what was the temperature according to a Centigrade thermometer at the same time and place?

$$(92 - 32) \times \tfrac{5}{9} = 33\tfrac{1}{3}. \quad \text{The temperature was } 33\tfrac{1}{3}° \text{ C.}$$

Observe, again, that the degrees are numbered from 0 both up and down the stem. To distinguish degrees below 0, they

are considered to be negative. Thus $-10°$ F. means $10°$ below the Fahrenheit 0.

Examples. — 1. What temperature C. corresponds to $-15°$ F.?

$$(-15-32)\times\tfrac{5}{9}=-26\tfrac{1}{9}.\quad \text{Hence } -15°\text{ F.}=-26\tfrac{1}{9}°\text{ C.}$$

2. Find the temperature on Fahrenheit scale equal to $-40°$ C.

3. Mercury freezes at $-38.8°$ C.; what is its freezing point on Fahrenheit scale?

4. Mercury boils at $350°$ C.; what is its boiling point on Fahrenheit scale?

i. It is evident from the last two examples that some other substance than mercury must be used to measure temperatures below $-38°$ C. and above $350°$ C. For the lower temperatures alcohol is often used; its freezing point is $-130°$ C.; and for the higher, metals are sometimes employed. But air is much better for the purpose than alcohol or metals. In fact, the air thermometer is the only means to measure very low or very high temperatures with accuracy.

Experiment 58. — *Object.* To test the accuracy of the freezing point on a thermometer scale.

Fig. 122 represents the arrangement of apparatus. Support a funnel, *f*, by a wide-mouth bottle. Support a thermometer, *t*, with its zero point just below the rim of *f*. Wash some good ice and crush it by inclosing it in cloth and pounding it with a hammer. Pack the well crushed ice around the bulb and stem, leaving the zero mark just visible above it. The ice will slowly melt, and the water will drain away into the bottle, thus leaving the thermometer all the time exposed to *melting ice*.

Watch the shortening of the mercury thread, and when the top has become stationary, read the scale, using a magnifying glass to enable you to estimate the tenths of a degree. The difference between this reading and zero will be the *zero error* of the thermometer.

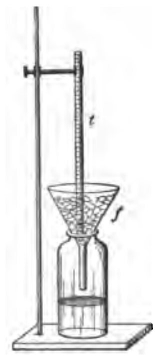

Fig. 122.

Experiment 59. — *Object.* To test the accuracy of the boiling point on a thermometer scale.

A wide-mouth flask, *F* (Fig. 123), is fitted with a stopper, through which passes the end of a tube, *T*, long enough to take in the boiling-point mark

when the bulb of the thermometer is about 1.5 cm. above the surface of the water, the flask being about one half full. The upper end of *T* is to be closed with a two-hole stopper. One hole contains the end of an elbow tube, *O*; through the other the thermometer is inserted. By this apparatus the bulb and stem of the thermometer may be heated to the temperature of the steam which must issue from *O*, and this is the same as that of the boiling water. Boil the water briskly, watch the mercury, and when it has become perfectly stationary, read the scale, using a magnifier to estimate the tenths. This gives the boiling point under the existing atmospheric pressure.

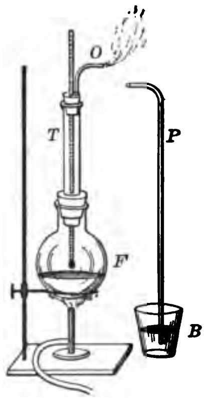

Fig. 123.

Experiment 60. — *Object.* To discover the effect on the boiling point of increasing the pressure on the liquid, and to make the necessary correction.

Use the long tube, *P*, and a beaker, *B*, containing mercury about 4 cm. deep. Join the upper end of *P* to *O*, and then insert the lower end of *P* into *B*. The steam must then pass through *P*, and the back pressure of the mercury in *B* will be exerted on the water in *F*. Boil the water briskly, and note the reading of the scale. This gives the boiling point under the additional pressure of the mercury in *B*. You should find that the boiling point rises if the pressure on the liquid is increased.

So the boiling point, found by the preceding experiment, *should be corrected* for atmospheric pressure; that is, we should find what it would be if the pressure were the standard 76 cm. (§ 75, *e*). To do this:

Read the barometer, take the difference between this and the standard 76 cm., and divide by 2.68. The quotient is the correction to be made, because it has been found that a difference of about 2.68 cm. in pressure makes a difference of 1° C. in the boiling point. This correction must be *added*, if the pressure is less than the standard, and *subtracted* if the pressure is greater.

Example. — A thermometer gives the boiling point of water as 99.5° C. when the barometer reading is 76.5 cm.; what correction should be made? What is the error of the thermometer?

$76.5 - 76 = .5 \qquad .5 \div 2.68 = .19$ nearly.

The correction to be made = .19° C.

Boiling point observed	99.5° C.
Correction to be subtracted	.19° C.
Boiling point at standard pressure	99.31° C.
Boiling point error of the thermometer . .	.69° C.

92. **Quantity of Heat.** — *a.* It is very difficult to measure the quantity of heat a body gives up in cooling, because a warm body scatters its heat among all the things, colder than itself, which it touches. We may direct the heat from a warm body into some one other body colder than itself, with all possible care to prevent it from going elsewhere, and yet some of it will escape in spite of our efforts. But by using proper vessels the loss may be made comparatively small.

Vessels for conducting experiments in the measurement of heat are called *calorimeters.*

One simple form of calorimeter is shown in section in Fig. 124. A cylindrical vessel, about 12 cm. high and 8 cm. in diameter, made of thin, polished, sheet metal,—copper is best,—is placed inside a wooden box, and loosely packed all around with wool or cotton. Through the wooden cover are two holes, one for the insertion of a thermometer, the other for a stirrer. A warm body put into the inner vessel will lose its heat very slowly, because the thin vessel will take but little to make it as warm as the body within, while the wool and wood transmit heat at a very slow rate.

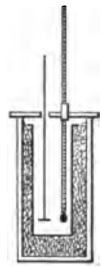

Fig. 124.

Experiment 61. — *Object.* To compare the quantity of heat given up by warm water with the quantity received by cold water, when equal masses of the two are mixed.

We may obtain very nearly equal masses of water by taking equal volumes, since 1 cc. of water is nearly 1 g. (§ 4, *h*).

Put about 200 cc. of warm water, at about 40° C., into the calorimeter, noting the exact volume. Put an equal volume of water, at the temperature of the room, into a beaker. Note the exact temperature of the cold water first, then of the warm water, and immediately pour the cold water into the calorimeter. Mix the two portions thoroughly with the stirrer, and take the temperature of the mixture. In one experiment the record stood as follows:

Warm water	200 cc. at 40° C.
Cold water	200 cc. at 21° C.
Mixture	400 cc. at 30° C.

In that case the warm water was cooled 10° C., and the cold water was warmed 9° C. In like manner, see if, in your experiment, the heat received by the cold water was nearly equal to that given up by the warm water.

But there were defects in the experiment not to be overlooked:

1. The masses taken were not exactly equal, because cold water is denser than warm water (§ 6, *a*, *b*).

2. A little of the heat from the warm water went to warm the calorimeter, the thermometer, and the stirrer, instead of into the cold water. On both these accounts the temperature of the mixture is not so high as it would otherwise have been. A small difference between the heat given and the heat received may be accounted for in this way. Making allowance for this small quantity, well made experiments prove the following statement:

b. The quantity of heat that makes a temperature change of 10° from 40° down the scale, will make almost exactly the same change of 10° from 20° up the scale. Or in general, *equal temperature changes in a given mass of water in different parts of the scale are produced by very nearly equal quantities of heat.*

The C. G. S. unit of heat is the quantity of heat that will raise the temperature of 1 g. of cold water 1° C. This unit is called a *gram-degree*, or *calorie.*

Experiment 62. — *Object.* To compare the quantity of heat given up by warm water with that received by cold water, when unequal masses are mixed.

Put about 200 cc. of water, at about 50° C., into the calorimeter, and about 300 cc., at the temperature of the room, into a beaker. Note the volumes and temperatures. Mix the two and take the temperature of the mixture. Make your record and study the results as suggested below:

Mixed 180 cc. water at	50° C.
With 320 cc. water at	20° C.
Found 500 cc. mixture	30° C.

While the temperature of the warm water was lowered 20°, that of the cold water was raised only 10°. These *temperature changes* are very unequal. To compare the *quantities of heat* in such a case we must measure them in gram-degrees (*b*). The number of gram-degrees is the product of the mass in grams by the temperature change in degrees. Thus:

From the warm water went	$180 \times 20 =$	3600 gram-degrees.
To the cold water went	$320 \times 10 =$	3200 gram-degrees.
Apparent loss of heat	$=$	400 gram-degrees.

It is easy to see that the observed results cannot be exact. Two defects of the experiment have been pointed out (Experiment 61). There is a third source of error: The readings of the thermometer are not exact. An error of .5° C. in the temperature of the warm water would make a difference of 90 gram-degrees. If the reading is taken too soon after inserting the thermometer, it is too low. By taking account of these defects the apparent loss of 400 gram-degrees may fairly be explained.

c. Such experiments, when well made, show that *the heat given off by any mass of water cooling* 1° *is equal to the heat required to raise the temperature of an equal mass of water* 1°. But it has been shown that this law is not exactly true unless the temperatures of the two masses are in the same part of the scale. For example: The heat required to raise 1 g. of water from 0° C. to 1° C. is a little more than that required to raise it from 10° C. to 11° C.[1]

d. The heat that raises the temperature of a calorimeter 1° is called its *water-equivalent.*

In one case it was found by experiment that 4.18 gram-degrees would raise the temperature of the calorimeter 1° C. But 4.18 gram-degrees will raise the temperature of 4.18 g. of water 1° C. (*b*). Hence that calorimeter would be counted as 4.18 g. of water in all temperature changes taking place within it, and in every experiment with it, 4.18 g. would be added to the mass of the water used, in order to allow for the heat which it takes.

The water-equivalent may be computed by multiplying the mass of the calorimeter, found by weighing, by the quantity of heat which will raise 1 g. of its substance 1°, found in tables of what are called *specific heats* (§ 94, *d*). Thus: The mass of a copper calorimeter was found to be 40 g., and the table

[1] Hence the definition of the gram-degree, as the quantity of heat required to raise the temperature of 1 g. of cold water 1° C., is not precise. "No definite temperature has been agreed upon for the cold water" (Everett's *C. G. S. System of Units*, 1891, pp. 98, 104). But if the gram-degree is equivalent to 42,000,000 ergs, then, according to Rowland, the standard temperature of the cold water is 10° C.

gives us .095 as the factor for copper. Then the water-equivalent is $40 \times .095 = 3.8$ calories.

Experiment 63. — *Object.* To find the quantity of heat required to raise the temperature of 1 g. of lead 1° C. (specific heat of lead).

Method. Mix a known mass of hot lead with a known mass of cold water. Find the gram-degrees which the lead gives to the water, and divide by the mass of the lead.

Operations. Use about 75 cc. of water, and about 300 g. of lead in the form of fine shot. To heat the shot, put it into a wide test tube, insert the bulb of a thermometer among the shot, place the tube in a beaker of water, and keep the water boiling until the thermometer shows that the temperature will rise no further. The water should be so deep that the lead is all below the surface. In the mean time measure the cold water into the calorimeter. Note its mass, counting 1 cc. = 1 g.; also the water-equivalent of the calorimeter, which, if not given you, find as described in the preceding paragraph (*d*). Then note the temperature of the shot. Keep the water boiling, but remove the thermometer and cool it in cold water. Wipe it, and take the temperature of the water in the calorimeter. Finally, grasp the tube, and immediately pour the shot, without loss, into the calorimeter, without splashing the water. Insert the thermometer, stir the water and shot, and take the highest temperature that the thermometer reaches. Record the observations as follows:

Mass of the lead	—— g.	M
Mass of the water if 1 cc. = 1 g. + water-eq. of the calorimeter	—— g.	m
Temperature of the hot lead	——° C.	T
Temperature of the cold water.	——° C.	t
Temperature of the lead and water . . .	——° C.	t_1

Make the computations as follows:

Temp. change of the water, $t_1 - t$ . . .	——° C.	A
∴ Heat received by the water, $m \times A =$ . .	—— gr.-deg.	B
Temp. change of the lead, $t_1 - T$.	——° C.	C

∴ M grams lead cooling $C°$ give up B gr.-deg.

and M grams lead cooling 1° give up $\frac{B}{C}$ gr.-deg.

and 1 gram lead cooling 1° gives up $\frac{B}{CM}$ gr.-deg.

Hence it takes $\frac{B}{CM}$ gram-degrees to raise the temperature of 1 g. of lead 1° C.

93. **Queries.** — How much heat would be required to raise the temperature of 1 kg. of lead 10° C.? How much heat would be required to raise the temperature of 1 kg. of water 10° C.?

At 60° or any other temperature, which contains the most heat, a given mass of lead or an equal mass of water?

94. **Specific Heat.** — *a.* The quantity of heat required to raise the temperature of a *unit mass* of any substance 1°, is called the *specific heat* of that substance.

If the temperature is measured in degrees Centigrade and the mass in grams, then the specific heat of a substance is the number of gram-degrees (calories) required to raise the temperature of 1 g. 1° C.

Thus experiments like Experiment 63, but made with care and skill, have shown that it takes .032 gram-degrees to raise the temperature of 1 g. of lead 1° C., while it takes .095 gram-degrees for 1 g. of copper. These quantities are the specific heats of lead and copper, respectively. Of course the specific heat of water is 1 gram-degree; this is greater than that of any other known substance except hydrogen.

b. The quantity of heat required to raise the temperature of *any body* 1° is called the *thermal capacity* of that body. It is computed by multiplying the specific heat of its substance by the mass of the body. Thus the thermal capacity of a bar of lead whose mass is 10 kg., or 10,000 g., is $.032 \times 10{,}000 = 320$ gram-degrees. That is to say, it will take 320 gram-degrees of heat to raise the temperature of the bar 1° C.

Examples. — 1. What is the thermal capacity of an iron kettle whose mass is 5 kg., the specific heat of iron being .11?

Ans. $(.11 \times 5000) = 550$, gram-degrees.

2. What is the thermal capacity of 4 kg. of water?

3. If the 4 kg. of water be heated in the iron kettle, from 20° C. to boiling point of the water, how much heat will be taken from the fire?

The kettle will take $.11 \times 5000 \times (100 - 20) =$ 44,000 gr.-deg.
The water will take $1 \times 4000 \times (100 - 20) =$ 320,000 gr.-deg.
∴ Heat required . . . . 364,000 gr.-deg.

4. Compute the water-equivalent of the kettle.

c. The quantity of heat involved in any temperature change is the product:

$$\text{Specific heat} \times \text{mass} \times \text{temperature change}.$$

The art of measuring the quantities of heat involved in producing temperature changes in bodies is called *calorimetry.* Thus the experimental operations to determine specific heat are processes in calorimetry. There are many different methods used in calorimetry; that in the foregoing experiments is known as the *method of mixtures.*

To find the specific heat of metals, and other solids which are not dissolved by water, the student may proceed as in Experiment 63. If the substance is a liquid which does not combine with water, the student can proceed as in Experiment 62. For other methods consult books on Heat.

d. The specific heats of a few substances, true to the nearest thousandth of a calorie, are given in the following list for reference:

Hydrogen	3.409	Copper	0.095
Water	1.000	Lead	0.031
Ice	0.504	Mercury	0.033
Air	0.237	Brass (hard)	0.086
Turpentine	0.426	Iron (0° to 100°)	0.110

95. **Studies.** — 1. The mass of a copper calorimeter was 30.32 g., and it contained 250 g. of water at 15° C. Afterward 150 g. of water at 98° C. was added. What was the final temperature?

Let t stand for the final temperature.

$$(250 + .095 \times 30.32) \times (t - 15)$$
$$= \text{heat received by cold water and calorimeter};$$
$$150 \times (98 - t) = \text{heat given up by warm water};$$
$$\therefore (250 + .095 \times 30.32) \times (t - 15)$$
$$= 150 \times (98 - t).$$

Ans. The final temperature, t, was 45.9° C.

2. 250 g. of water at 0° C. was put into a brass calorimeter whose mass was 40.25 g.; 400 g. mercury at 99° C. was added. The final tem-

perature was 4.9° C; what is the specific heat of mercury according to this experiment (§ 94, *c*)?

$$\left.\begin{array}{l}\text{Specific heat} \times \text{mass} \times \text{change in}\\ \quad\text{temperature of mercury}\end{array}\right\} = \left\{\begin{array}{l}\text{specific heat} \times \text{mass} \times \text{change in}\\ \quad\text{temperature of water.}\end{array}\right.$$

3. If we have an iron calorimeter, whose mass is 45.6 g., containing 100 g. of water at 15° C., what mass of iron at 68° C. must be immersed to cause the final temperature of all to be 20° C.?

4. If 10 kg. of water at 18° C. be placed in a room measuring 4 × 4 × 3 meters, in which the air is at 0° C., to what temperature would the water be able to warm the air, if its heat could go to no other body? (The density of air at 0° C. may be taken as 1.3 g. per liter.)

Ans. 7.26° + C.

5. How much heat is required to raise the temperature of 1 gallon (10 pounds) of water from 60° F. to the boiling point, in an iron kettle whose mass is 8 pounds? *Ans.* 1653.76 Eng. units.

6. If the least possible amount of heat is to be used to raise the temperature of 5 kg. of water from 0° C. to the boiling point, would you choose an iron or a brass kettle, of equal mass, in which to heat it? Why? If the mass of each kettle is 4 kg., how much heat would be saved by the choice?

7. Why should a hot-water bag be preferred to a stone of equal mass as a foot warmer?

8. Why do extremes of heat and cold in inland places exceed those of places near large bodies of water?

THE TRANSMISSION OF HEAT.

96. **Conduction, Convection, and Radiation.** — *a.* If one end of a wire — iron, copper, or brass — is held in a flame, the fingers, at the other end, will in due time receive heat. It will be found that the wire is heated all the way along, but less and less at greater distances from the flame. Try it.

In this case some of the energy of the flame is taken by the end of the wire, and passed along, from molecule to molecule, to the other end. The transmission of heat from molecule to molecule is called *conduction* of heat.

By conduction, heat is transferred from the warmer to the colder parts of the same body, or from one body to a colder body in contact with it.

b. If the hand is held above a flame, an upward current of warm air is felt. In this case some of the energy of the flame is taken by the molecules of air, which retain it while they go from the flame, and part with it again on contact with the hand. The heat is transferred by the air only as the molecules themselves are transferred. The transmission of heat by currents of heated molecules is called *convection* of heat.

By convection, heat is diffused throughout bodies of gases and of liquids. Evidently it cannot occur in solids.

c. If the hand is held alongside a heated body, or below it, or elsewhere in its vicinity, heat will be felt. It is found also that in a vacuum heat passes from body to body when they are not in contact.

In this case there can be neither conduction nor convection. The heat is transmitted by the ether (§ 20, *c*), which is thrown into undulation by the energy of the molecules of the hot body. The transmission of heat by undulations of the ether is called *radiation* of heat.

By radiation, heat is going from every body to every other continually. If a body receives from others more than it gives to them, it becomes warmer; if it gives more than it receives, it becomes colder.

Conduction, convection, and radiation are the three distinct modes in which thermal energy is transmitted from body to body. Bear in mind that radiant heat has not been the subject of our study, nor will it be until we reach the study of light (§ 89, *a*, *b*).

97. **Conductivity.** — *a*. With one hand hold a small glass tube and with the other an iron rod, about the same size, across the top of a gas flame. The glass may be kept red hot for a long time within one or two inches from the fingers without causing discomfort, while the iron soon becomes unpleasantly hot at a much greater distance. This shows that iron transfers heat more rapidly than glass.

A similar difference is found to exist among other substances. Those which transfer heat rapidly — that is to say, a large quantity to considerable distance in a short time — are called *good conductors,* while those which transfer heat slowly are called *poor conductors.* The property of matter by virtue of which it transmits heat by conduction is called *thermal conductivity.*

b. If we heat one end of a small copper wire (No. 21) about 15 cm. long, we find the other end becoming warmer and warmer for a time, and then keeping a steady temperature. Try it. In fact, all points along the wire reach a stationary temperature. No doubt the heat continues to travel along the wire as much as at first. Each point receives heat at the same rate as before, but its temperature does not rise. Hence it must be giving away its heat as fast as it receives it.

The heat is lost from the wire at every point, and from other bodies in similar circumstances, in three ways:

1. Some goes by conduction to the next adjacent molecules.
2. Some is taken away by convection in the air.
3. Some is given off by radiation (§ 89, *b*).

The rate[1] at which the heat flows through any substance, *after its temperature becomes stationary,* represents the conductivity of that substance.

Experiment 64. — *Object.* To compare the thermal conductivity of different metals by the Ingenhausz method.

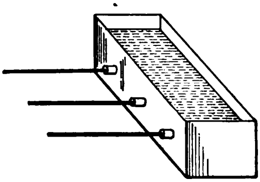

Fig. 125.

The apparatus consists of a trough to contain hot water, with small tubes in the side, through which rods of different metals, — iron, copper, and brass are convenient, — fixed in with corks, project into the water (Fig. 125). The rods should be equal in length, about 12 cm., and in diameter about .5 cm., and project equal distances

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[1] By rate we mean the quantity of heat that goes through a plate of substance 1 cm. square and 1 cm. thick in 1 second, when the two faces of the plate differ in temperature by 1° C.

into the trough. Why? They should be evenly covered with a thin coating, by inserting them in melted wax. The trough is then filled with boiling water. The melting of the wax shows the progress of the heat along the rods. The *rate* at which the melting travels along a rod denotes the rise of temperature, and not necessarily the conductivity of the metal, because the specific heat may be different, so that a smaller quantity is required by one than another for the same temperature change. The *distance* to which the melting extends represents the conductivity. When the melting ceases, measure the distance that the wax melted on each rod. Make more than one trial, tabulate the results, and compare the conductivities.

c. Solids, as a class, are better conductors than liquids. Among solids the metals are the best conductors, but they differ greatly among themselves. Liquids, excepting mercury and melted metals, are very poor conductors. As for gases, their conductivity is extremely small. In fact, it is still ~~doubtful whether they conduct~~ heat at all.)

(?)

d. In the practical affairs of life, whenever a body is to be protected against heat from outside, or against loss of heat from inside, they should be separated from outside bodies by poor conductors. On the other hand, whenever heat is to be transmitted either way, good conductors should be used.

e. A judicious application of this principle will explain many every-day phenomena, and solve many problems relating to the use of heat.

In winter the person is to be protected from cold; that is to say, its heat is to be kept from passing rapidly out. Then woolen garments are worn, because wool is a poor conductor. In summer the person is to be protected from its own heat, which accumulates because the warm air takes it off more slowly than it is generated. Then cotton garments are preferred, because cotton is a better conductor than woolen.

Blocks of ice wrapped in woolen cloth melt slowly, even in summer. But why should woolen be worn to keep the person warm, and used also to keep the ice cold? Vegetables inclosed in wooden boxes will not freeze so readily as if exposed to air

or inclosed in metal. Furnaces are lined with fire brick to keep the heat in; ice boxes are built with double walls, filled in with air, or some fibrous or porous material like asbestos, to keep the heat of the summer air out.

Copper is a much better conductor than iron; hence copper is a better material for boilers and kettles. It is less durable, and more easily corroded by organic acids, hence not so desirable for some culinary purposes; but it is more economical of heat.

We know that water is readily heated throughout by applying heat to the bottom of the vessel which contains it. But how can this be so if water is such an extremely poor conductor? The fact is explained as follows:

98. **Convection.** — *a.* That portion of a fluid which is heated by contact with a hot body is expanded; its density is lessened, and hence it is pushed upward by adjacent portions, on the principle of buoyancy (§ 79, *b*, *c*). Hence water or air, in a vessel heated from below, will be pushed upward by colder portions, which take their place only in turn to be driven away. Currents of warmer fluid flow away from the source of heat, and other currents of colder portions flow toward it. Try water. Put fragments of blue litmus at the bottom, and heat gently with small flame. It is by these currents that the heat is distributed. They are called *convection currents*, and this mode of distributing heat throughout a body is called *convection.*

b. By convection the air in a room is heated by a stove or radiator. Also, by convection currents, water in boilers becomes heated throughout. Convection currents may flow downward. For example, if a basin of ice is floated on warm water, currents of cooled water will fall away toward the bottom.

c. The ventilation of rooms is accomplished by producing convection currents. The air of a living room is warmer than that outside. Hence a warm flue or chimney will carry off the

warm, impure air, provided the colder air can enter to push it out. The cold air is usually expected to enter through the chinks around the door and windows, but a better plan is to provide special openings for it near the floor, and then to warm it on its way, by having it pass over heated pipes, to prevent it from settling as a cold stratum over the floor.

d. The hot-water heating of houses is accomplished by producing convection currents in water. Fig. 126 illustrates the principle involved in the method. Suppose a vessel, *B*, with a pipe, *F*, extending upward from the top, and connected with branch pipes, *H* and *R*, leading back to the bottom. Let *B* and these pipes be filled with water, leaving an opening at the highest point for the escape of air which is contained in the water. Then if *B* is heated, the colder water in *R* will enter at the bottom, while the warm water rises in *F*, and flows over through *H* and *R* to reënter at the bottom of *B*. The flow will continue so long as *B* is warmer than *R*, and the pipes at *H* will continually take heat from the water, and give it off to the room by radiation and contact with air.

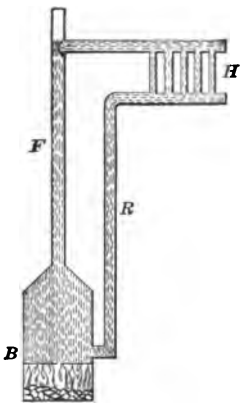

Fig. 126.

A house-heating apparatus consists of a boiler and furnace, *B*, placed as low as possible, with main pipes, *F*, reaching the upper parts of the building, and branch pipes to carry the water through coils, or clusters of metal tubes, *H*, called *radiators*, in the rooms to be heated, from which return pipes, *R*, lead the water back to the boiler.

If 10 pounds of water enter *H* at 85° F., and leave it at 70° F., then 150 English units of heat have been given by the water to the coil, and these 150 units are given out by the coil to warm the room.

EFFECTS OF HEAT—EXPANSION.

99. **Work done within a Body.** — The thermal energy which enters a body is expended in doing various kinds of work. It changes the temperature, changes the volume, and may produce liquefaction and vaporization. We are now to describe the last three of these effects.

100. **Expansion.** — *a.* That an iron ball is larger when hot than when cold may be proved by experiment with a metal

Fig. 127.

ball and ring, represented by Fig. 127. The ring is made just large enough to let the ball, when cold, pass through it; it is found to be too small when the ball is hot. With few exceptions solids are expanded by heat. That liquids and gases are expanded by heat has been shown already (§ 41). What we should next study is the expansion of different substances when heated alike.

b. The behavior of two solids when heated under the same conditions may be studied by riveting together two narrow strips of thin metal, iron and copper, of equal lengths, and then plunging the compound bar into boiling water, or heating it in a current of steam. The strips should be about 20 cm.

long, and riveted at every 3 cm. The compound bar is found to be bent, with the copper on the convex side. Clearly these two metals do not expand at the same rate, and it is easy to see which expands most with equal temperature changes.

Experiment 65. — *Object.* To study the expansion of two liquids when heated alike.

Select two 6-inch test tubes of as nearly equal capacity as possible, two corks which fit tightly without entering far, with two glass tubes of small and equal bore, about 20 cm. long, as shown in Fig. 128. Fill one test tube to the brim with water, and insert the cork. The water may quite easily be made to stand a few centimeters up in the tube, at *a*, without a bubble of air below the cork. Fill the other test tube in the same way with alcohol. Next immerse both test tubes in one beaker of water, at about 55° C., and watch the liquids at *a*. You will be convinced that these two liquids do not expand at the same rate, and, by measuring *ab*, can make a rough estimate of their relative rates of expansion for equal temperature changes. The estimate will be nearer the true value as the tubes are more nearly alike.

Fig. 128.

Experiment 66. — *Object.* To find the apparent rate of expansion of a liquid (coefficient of expansion).

By *rate of expansion* we mean the enlargement of 1 cc. of substance when heated 1° C.

The apparatus is represented by Fig. 129. *A* is a glass tube to contain the liquid. It is about 30 cm. long and .6 cm. inside diameter. It is closed at one end with the bottom as flat as possible. A thermometer, *t*, is bound to *A*, with its zero at the closed end, by bands, *r*, cut from the end of a rubber tube. There should be no danger of its slipping down or up. *C* is a tall jar to contain warm water by which to heat the liquid in *A*.

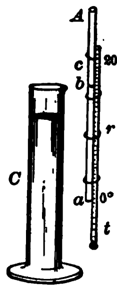

Fig. 129.

Introduce as much liquid into *A* as will make the length, *ab*, such that when inserted in *C*, the upper end will be below the surface of the water. Its volume is to be noted in cubic centimeters, and also by the number of thermometer divisions in its length. Since the tube *A* is supposed to be uniform in its cross section the thermometer divisions represent equal volumes. Why? Take the temperature just before inserting *A* in the water. Take it again *when it has reached its highest point.* Results may be noted briefly as in the following example:

Volume of alcohol at 26° C. . . 5 cc.
Volume of alcohol at 26° C. . . 137 thermometer divisions.
Volume of alcohol at 53° C. . . 141 thermometer divisions.
$\therefore$ 5 cc. of alcohol heated 27° C. expand 4 thermometer divisions.

But 1 thermometer division $= \frac{5}{137}$ or .0365 cc.,
and 4 thermometer divisions = .146 cc.

$\therefore$ 5 cc. alcohol heated 27° C. expand .146 cc.

$\therefore$ 1 cc. alcohol heated 1° C. expand $\frac{.146}{5 \times 27}$ or .00108 cc.

According to this experiment, any quantity of alcohol between 26° C. and 53° C. expands at the average rate of .00108 of its volume per degree.

But this is not the true rate of expansion of the liquid, because the glass tube expands at the same time. It is the *difference between the rates* of the liquid and the glass. It must be corrected by adding the rate of glass, which may be found in a table of coefficients of expansion.

c. The following general facts or laws have been discovered by experiment:

All bodies, with few exceptions, are enlarged by heat. Water at 0° C. is an exception. It contracts when heated until 4° C., after which it expands.

Solids as a class expand less than liquids, and liquids less than gases, with equal rise of temperature.

Each solid and each liquid has its own specific rate of expansion, but all gases expand at the same rate.

The rate of expansion of a solid increases a little as the temperature rises; that of a liquid increases much more; but the rate of a gas is constant, the expansion of a cubic centimeter being the same whether the gas is heated from 0° to 1°, or from 100° to 101°.

101. **Coefficient of Expansion.** — *a.* The small fraction of itself which a unit volume of any substance at 0° C. expands when heated 1° C., is called its *coefficient of cubical expansion.* The small fraction of its length at 0° C. which a unit length of a solid expands when heated 1° C. is called its *coefficient of linear expansion.* Thus according to Experiment 66, .00108 is the coefficient of cubical expansion of alcohol.

It has been found that a cast iron bar a unit long at 0° C., will increase in length .000011+ of itself when heated 1° C. Hence the coefficient of linear expansion of cast iron is .000011+.

The coefficient of cubical expansion is almost exactly three times the coefficient of linear expansion in every case. Thus the cubical coefficient of cast iron is .000034.

Example.—If an iron bar is 3 m. long at 0° C., how long is it at 100° C.? The linear coefficient of cast iron is .000011.

The expansion of 1 m. is .000011 m. if heated 1° C.

The expansion of 1 m. is .000011 × 100 if heated 100° C.

$\therefore$ 1 m. at 0° C. becomes 1 + .0011 m. at 100° C.

$\therefore$ 3 m. at 0° C. becomes 3 (1 + .0011) m. at 100° C.

Ans. At 100° C. the bar is 3.0033 m. long.

b. We have seen (§ 75, *f*) that the height of the barometric column does not truly represent the pressure of the air unless the temperature is 0° C., or its equivalent, 32° F. It is too high if the temperature is above 0° C., and too low if the temperature is below 0° C. Why? But we can easily correct it. For example: On one occasion the height of the column was observed to be 77.5 cm., and the temperature to be 20° C.; what was the height due to atmospheric pressure?

The coefficient of expansion of mercury is .00018.

Hence, 1 cm. mercury expands .00018 cm. for 1° C.;

1 cm. mercury expands .00018 × 20 for 20° C.;

77.5 cm. mercury expands .00018 × 20 × 77.5 for 20° C.

Hence the *expansion* of the barometric column was .279 cm.

And 77.5 − .279 = 77.22 cm., the height due to atmospheric pressure alone, if we neglect the expansion of the scale.

For temperatures below 0° C. the correction must be added.

c. Since the volume of a given mass of any gas depends so much on its temperature (why?), no definite value can be given to it unless the temperature is stated. The standard temperature is 0° C., or the freezing point of water. If the

temperature is above 0° C., the measured volume is too large; if below 0° C., the volume is too small. But we can easily correct it. For example:

On one occasion a chemist obtained 1.5 liters of carbon dioxide, at 18° C., from marble, by means of an acid; what was the volume at standard temperature?

The coefficient of expansion of all gases is $\frac{1}{273}$, or .00366.

Hence, 1 cc. of the gas expands .00366 cm. for 1° C.;
1 cc. of the gas expands $.00366 \times 18$ for 18° C.;
1500 cc. of the gas expands $.00366 \times 18 \times 1500$ for 18° C.

The *expansion* of the 1.5 liters was 98.82 cc.

And $1500 - 98.82 = 1401.18$ cc., the corrected volume of the carbon dioxide.

EFFECTS OF HEAT — FUSION.

102. **Fusion.** — Fusion is the change of a substance from the solid to the liquid state by heat. The temperature at which fusion occurs is called the *melting point*. The reverse change — that is, the change from the liquid to the solid state — is called *freezing*, and generally occurs at the same temperature.

Three important facts relating to fusion must now be considered:

1. The change in volume which takes place.
2. The temperature at which it occurs.
3. The amount of energy expended to produce it.

Experiment 67. — *Object.* To discover what change in size occurs when solids melt or liquids freeze.

Fill a small bottle, holding about 50 cc., *full* of water; cork it tightly, and bury it in a mixture made of crushed ice with about one half its mass of salt. Then fill a test tube nearly full of melted paraffin, and stand it upright — not buried — in the same mixture. Fix another test tube of melted beeswax in the same way. These liquids will slowly freeze, and when they have solidified, you can discover evidences of expansion or contraction, and compare the changes of volume in the three substances.

Nearly all fusible solids behave like the paraffin and beeswax. The behavior of water is one of the few exceptions to the law.

Experiment 68. — *Object.* To discover what changes in temperature occur when bodies melt or freeze.

Fill one beaker two thirds full of clean crushed ice; insert a thermometer, and note its temperature. Pour in water to fill the beaker to the level of the ice. Stir the mixture well, but carefully, with the thermometer until the ice is all melted, and observe from time to time the change in temperature, if any occurs.

Most fusible substances, having reached their melting point, behave like water in respect to temperature; but some, like glass, pass through a pasty condition on their way to the liquid state; and some, like camphor and iodine, if *heated slowly*, do not melt, but vaporize. Try it.

Experiment 69. — *Object.* To find the melting point of beeswax, tallow, or paraffin.

Draw out a glass tube to a small bore (.1 cm.) and fuse the end shut. Put a little of the solid into the tube, and melt it by inserting in hot water until the small tube is filled. Bind the tube to a thermometer, with its narrow part alongside the bulb. Notice that the substance is opaque. Place it in a beaker of water and warm it very slowly, stirring the water with the thermometer. Note the temperature at which the substance begins to be transparent, and then let the water cool, and note the temperature at which the substance begins to become opaque. The mean of these two temperatures is the melting point. Repeat the observations twice, tabulating the three sets, and take the mean of the three results.

103. The Laws of Fusion. — *a.* The facts relating to fusion may be summed up in the following laws:

1. *A fusible solid begins to melt at a definite temperature, always the same, for the same substance, if the pressure is constant.*[1]

Thus the melting point of ice is 0° C.; of white wax, 65° C.; of cast iron, about 1200° C.; of mercury, – 39° C.; of alcohol, – 130° C.

2. *The temperature of a substance remains unchanged while it is melting, but the volume changes. Most substances expand while melting.*

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[1] The effect of pressure is slight. Thus the pressure of an atmosphere will raise the melting point of ice about $\frac{1}{100}$ of a degree Centigrade.

Thus ice at 0° C., when melted slowly, becomes water, which is also at 0° C. All the heat absorbed by the solid is used to produce the liquid state. The heat that is absorbed by a body without any change in temperature is called *latent heat.*

3. *Each substance requires a definite quantity of heat per unit mass to hold it in the liquid state. During fusion this quantity is absorbed, and when the liquid solidifies, the same quantity is given out.*

Thus every gram of ice at 0° C. takes 80 calories of heat to melt it without warming it at all, and when the water freezes, every gram of it gives out 80 calories, to whatever it touches, without becoming colder. The latent heat of water is 80 units of heat per unit mass.

Water = ice + 80 calories of heat per gram.[1]

b. Water by melting or freezing lowers or raises the temperature of adjacent bodies. For example:

A block of 50 pounds of ice, while melting in an ice box, absorbs $80 \times 50 = 4000$ English units of heat from the interior. The loss of so much heat would reduce the temperature of 100 pounds of butter (sp. heat = .918) from 85° F. to about 41° F., far below its melting point. In this way perishable articles are protected from the injurious effects of summer heat.

Again, vegetables freeze at a little below the temperature of freezing water. Hence a pan of water in a cellar will protect such articles from frost. Thus if 100 kg. of water at 20° C. in a shallow pan should freeze solid, it would yield heat enough to keep the air of a small cellar above 0° C. for a considerable time. The truth of this is shown as follows:

100,000 g. of water from 20° to 0° yield 2,000,000 calories.
100,000 g. of water at 0° to ice yield 8,000,000 calories.

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[1] Or water = ice + $80 \times 42{,}000{,}000$ ergs of potential energy per gram (§ 92, *c*, footnote).

Hence the water would give 10,000,000 calories of heat to the cellar and its contents.

c. Freezing mixtures owe their cold to the liquefaction of their constituents. By the mutual action of ice and salt both are changed from the solid to the liquid state, and the heat required to do this is taken partly from their own substance and partly from whatever else may be in contact with them. Thus the mixture of crushed ice with about one half its mass of common salt, used in the ice-cream freezer, lowers the temperature of cream below its freezing point.

A similar effect is produced when salt is sprinkled on ice upon doorsteps and sidewalks, to melt it. The ice is melted, but the step or walk is made extremely cold, and chills the feet that press upon it.

104. **Studies.** — 1. Why do the feet become colder in walking over paths covered with melting snow than over the same paths covered with freezing water, or ice below its melting point?

2. Why does freezing weather come earlier in the season to places far inland than to those bordering lakes and oceans?

3. Why should the water pipes in houses be protected in winter from temperatures below 0° C., or be left unfilled?

EFFECTS OF HEAT — VAPORIZATION.

105. **Vaporization.** — *a.* Vaporization is the change of a substance from the liquid or solid to the gaseous state.

Vaporization is called *boiling* or *ebullition* if a liquid is agitated by bubbles of its own vapor produced by heat. It is called *evaporation* if a liquid becomes a gas without any agitation by bubbles, as alcohol and water do, when left in an open vessel. It is called *sublimation* if a solid becomes a gas without melting, as camphor and iodine do when gently heated.

b. The reverse change — the change of a gas to the liquid state — is called *liquefaction* of gases, or *condensation.*

106. **Ebullition.** — *a.* Three important facts relating to boiling must be considered:

1. The change in volume which takes place.
2. The temperature at which it occurs.
3. The quantity of energy expended to produce it.

b. Whenever a liquid is changed into gas there is a sudden and very large expansion. Of course the amount of expansion will depend on the pressure under which the change occurs (§ 84, *a*), but under ordinary atmospheric pressure, 1 cc. of water becomes about 1650 cc. of steam. No other liquid expands so much. Alcohol yields only about 528 times its own volume of vapor.

c. The temperature at which a liquid boils under the standard pressure — 76 cm. of mercury — is its *boiling point.*

Experiment 70. — *Object.* To find the boiling point of a liquid.

Fit up the apparatus (Fig. 130). A wide test tube, containing 10 cc. or 15 cc. of the liquid, is closed by a doubly perforated cork, with an elbow tube in one hole and a thermometer in the other. The bulb of the thermometer should be 2 cm. or 3 cm. above the surface of the liquid.

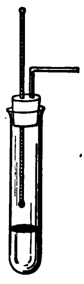

Fig. 130.

Boil the liquid by inserting the test tube in a beaker of another liquid, whose boiling point is higher than its own.[1] For liquids boiling below 100° C., water will do; for water, linseed oil may be used. Heat the bath gradually, and when the vapor issues freely from the elbow, read the thermometer. The observed boiling point, thus found, must be corrected for pressure (Experiment 60). Hence, read the barometer, and for every .1 cm. above or below the standard 76 cm., reckon .0373° C. This correction must be added, if the pressure is below 76 cm., and subtracted if it is above.

d. Since the temperature of a liquid does not rise during ebullition, it is evident that the heat received is all expended in converting the liquid into gas.

Experiment 71. — *Object.* To find the quantity of heat expended in changing 1 g. water at 100° C. into steam at 100° C. (latent heat of steam).

One method is founded on the fact that the condensation of steam to water restores the heat which produced the steam. Hence, if steam is

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[1] Combustible liquids, like alcohol and ether, must be heated at considerable distances from flame, else the vapor may take fire.

condensed in cold water, the water will be warmed, and if we measure the heat which the water receives, we find that which was expended in changing the water into steam.

The apparatus is represented in Fig. 131. About 150 cc. of water is to be boiled in the small flask *F*. The steam is to be led over into cold water in a calorimeter (Fig. 124) represented by *c*, which will condense it and be warmed by its latent heat. But some steam must be condensed along the way, and to keep the hot water thus formed from going into *c* with the steam, it is to be caught in a "trap," *t*. A side-neck test tube may be used for this purpose.

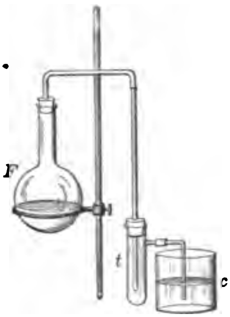


Fig. 131.

Operations. Set up the apparatus as shown, leaving the calorimeter out. Apply a gentle heat to *F*, and then proceed to fix the calorimeter. Find its mass. Add about 200 cc. of cold water, and find the mass of both. After steam has issued freely from the elbow of the trap *t* a little while, take the temperature of the water in the calorimeter, and at once insert the elbow tube as shown in the cut. Stir the water with the thermometer, and when its temperature has risen about 20° C. or 30° C., remove the elbow tube, and read the temperature quickly. Finally, find the mass of the calorimeter and water. The increase of mass is the mass of the steam which has been condensed.

The following example shows the notes and computations of an experiment:

Mass of the calorimeter (copper) . .	44.00 g.	
Mass of the calorimeter and cold water	250.00 g.	
∴ Mass of the cold water	206.00 g.	= 210.18 g.
Water value of calorimeter (44 × .095)	4.18 g.	
Temperature of cold water	17° C.	
Temperature of warmed water . . .	44° C.	
∴ Temperature change in cold water		= 27° C.
Mass of calorimeter and warm water .	259.56 g.	
∴ Mass of steam condensed		= 9.56 g.

It appears that 9.56 g. of steam, in condensing to water and then cooling 56° C. (100 − 44), yields enough heat to raise the temperature of 210.18 g. of water from 17° C. to 44° C., or 27° C. Hence:

Heat received by the cold water	= 210.18 × 27	= 5674.86 ca.
Heat derived from the 9.56 g. warm water	= 9.56 × 56	= 535.36 ca.
∴ Heat derived from the 9.56 g. steam	= 5674.86 − 535.36	= 5139.50 ca.
Heat derived from 1 g. steam		= 537.60 ca.

Hence 537.6 ca. are expended to change each gram of water at 100° C. into steam at 100° C. But there were sources of error in this experiment. The masses were not true beyond the .01 g., the temperatures were not true to less than 1°, and there were some losses by radiation and absorption. According to Andrews, the true value of the latent heat of steam is 535.9 gram-degrees. Its approximate value is 536 gram-degrees.

e. The purification of liquids is accomplished by distillation, which consists in boiling them and carrying their vapors over into clean receivers, where they are condensed. The vapors leave the boiler at their boiling points; while solids, or other liquids with higher boiling points, are left in the boiler.

f. The heating of houses by steam is accomplished by condensing steam in clusters of pipes — "radiators" — located in the several rooms. The apparatus consists of a boiler and furnace, from which main pipes lead steam to distant points, and branches carry it to the radiators. The steam condenses in these radiators, and gives up to them all its latent heat. The water then flows back to the boiler.

107. **The Laws of Ebullition.** — The facts relating to boiling may be summed up in the following laws:

1. *A liquid begins to boil at a definite temperature, always the same for the same liquid under the same conditions.*

2. *The boiling point rises if the pressure is increased.*

3. *The boiling point is raised by solids and lowered by gases dissolved in the liquid.*

4. *The boiling point in different vessels is not the same. It is higher as the adhesion (§ 47, b) between the liquid and the substance of the vessel is greater.*

5. *While a liquid boils, no change in temperature occurs, but expansion is very great.*

6. *Substances require different quantities of heat to hold them in the gaseous state under the same conditions. Each absorbs its own quantity when it boils, and when its vapor condenses, the same quantity is given off.*

Thus the latent heat of steam is about 536 ca. per gram; of alcohol, 202.4; of ether, 90.4.

108. **Evaporation.** — *a.* A liquid evaporates (§ 105, *a*) at all temperatures between its freezing and boiling points, but more rapidly as the temperature rises. The evaporation is due to the ceaseless activity of the molecules of the liquid (§ 31, *e*), and to the fact that their energy is greater than that of the air molecules with which they are in contact.

b. Evaporation takes place from the surface of a liquid. This is so because the molecules at the surface are impeded only by molecules of air, whose energy is less, while in the interior they impede and neutralize the motions of one another. Therefore, the rate of evaporation depends on the extent of surface exposed. On this account the evaporation of brine in the manufacture of salt, and of the sap of the maple tree, or the juice of the cane, in the manufacture of sugar, is carried on in large shallow pans.

c. Evaporation is retarded by pressure. A liquid evaporates more rapidly when the atmospheric pressure is less, and still more rapidly if the pressure is reduced by removing the air by means of an air pump. Hence vacuum pans are used for the concentration of sirups, especially such as are easily burned, since rapid evaporation is thereby secured at lower temperature.

d. Evaporation of water is retarded by water vapor already in the air. It is so because the water molecules in the air, darting in all directions, return to the liquid in great numbers. On this account a current of air over the surface of a liquid hastens evaporation. It is well known that a muddy street dries more quickly when the wind blows.

e. Evaporation reduces temperature. Moisten one finger, and wave the hand in the air. That finger becomes colder than the others. The water takes heat from the finger at the rate of 536 calories per gram to vaporize it (Experiment 71).

By the rapid evaporation of liquids with low boiling points, the most intense cold has been obtained. Artificial ice is made by evaporating liquid ammonia in ice machines.

109. **Studies.** — 1. A dampened sheet hung in a warm room will cool the air. Explain the fact.

2. If a gallon of water is to be boiled at the lowest possible temperature, will you select a tall and narrow, or a low and broad, vessel for the purpose? Explain.

3. It is found that the boiling point of water is about 1° C. lower for every 295 m. ascent above sea level; how will you account for this?

Compute the elevation of Quito, where the average boiling point of water is 90.1° C.

4. How much heat per minute can be given out by a radiator in which 100 g. of steam, at 100° C., is condensed to water every second, and leaves the radiator at 80° C.?

5. If the room to be warmed by this radiator measures $5 \times 5 \times 3$ m., the density of the air at 0° C. is 1.3 g. per liter, the specific heat of air, .237; and if only $\frac{1}{50}$ of the heat goes to warm the air, — the rest going to the walls and furniture, — what is the rise of temperature of the air per minute?

6. How many grams of water, at 100° C., would fill the same space as the 100 g. of steam at 100° C.? If this quantity leaves a radiator every minute at 80° C., how much heat does it give out per minute?

VIII. SIMPLE HARMONIC MOTION.

VIBRATIONS.

110. **Vibration.** — *a.* We have seen that if an elastic body is strained, but not too much, it will recover its normal size or shape when the stress is removed (§ 45, *a*, *b*). But this is only a part of the truth. The energy which strains the body is not exhausted by a single recovery, but by a series of strains and recoveries. While these last, the body is said to *vibrate.*

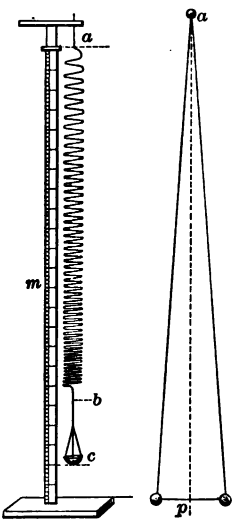


Fig. 132.

b. If a small mass, *c*, is hung on the end of a spiral spring, *ab* (Fig. 132), then pulled down a little way and let go, the spring will be shortened and lengthened many times before it comes to rest. Try it. If we cause a long pendulum, *ap*, to swing in a small arc, and compare the motions of *c* and *p*, we find them to be alike in one respect: In each case the motion is *alternately in opposite directions through the place where the body rests when there is no stress upon it.* Such motion is called *vibration.* It is also called *oscillation.*

Notice that the hook, *b*, also vibrates. In fact, all parts of the spring, from *a* to *c*, are vibrating together. The same is true of all parts of the pendulum from *a* to *p*.

c. The vibration of the spring may be explained as follows: The energy expended to depress *c* becomes potential in the

stretched spring. When the elastic spring recovers from the strain, this energy becomes kinetic. When it reaches its position of rest, this kinetic energy drives it onward, and the spring is again compressed, while the energy becomes potential. As the spring recovers from the new strain, the energy again becomes kinetic, drives its parts beyond their rest points, and in so doing, becomes potential again. These alternations between potential and kinetic energy, with the alternate strain in opposite directions, continue until the energy is exhausted. What becomes of it? A part is given to the air, and another part, which is absorbed by the molecules of the spring, becomes heat (§ 90, *e*). In bodies of little elasticity, the energy becomes heat rapidly, and vibration dies out quickly.

d. The vibrations of a cord may be illustrated as follows: Stretch a cord between two fixed points, about 1 m. apart. Strain this cord by pulling its middle point to one side, and

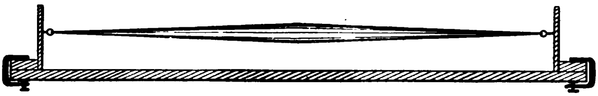


Fig. 133.

then release it. You should see (Fig. 133) that every part of the cord vibrates, though not all with the same amplitude, and be able to trace the alternations between potential and kinetic energy.

e. Notice this difference in the directions of the vibration described in paragraphs *b* and *d*. The motion of every part of the cord is at right angles to its length, that of every part of the spring (not of the wire) is in the direction of its length. This important difference is found in the vibrations of other bodies. Vibrations at right angles to the length of a vibrating body are called *transverse vibrations.* Vibrations in the direction of the length of the body are called *longitudinal vibrations.*

Experiment 72. — *Object.* To study vibration by means of a conical pendulum, and to represent the observed facts by a diagram.

A conical pendulum is a pendulum whose bob swings in the circumference of a circle.

1. Suspend a ball by a thread, which should be as long as practicable. Make it swing in a small circle, and count its rounds per minute. Make it swing in the diameter of the circle, — that is, as a common pendulum, — and count the complete vibrations (§ 69, *b*) per minute. Compare the two numbers.

Make the bob swing in a small circle. Stand a considerable distance away and put the eye on a level with the bob. Observe that it now *appears* to swing to and fro in a straight line, which is the diameter of the circle in which it moves. Notice also that the speed of the bob in the circle is uniform, but that it appears to increase and diminish alternately in the straight line.

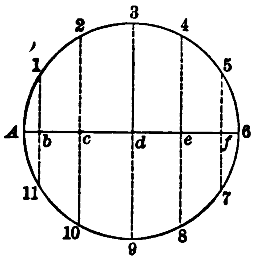


Fig. 134.

2. Next *represent the observed facts* by a diagram (Fig. 134). Draw a circle for the path of the pendulum bob, and a diameter for its apparent straight-line path. Mark on the half circumference an even number of equidistant points, 1, 2, 3, etc.; drop dotted perpendiculars from these to the diameter, and produce them to the circumference beyond. The points show the places of the bob at *equal intervals* of time during one round, and the feet of the perpendiculars *b*, *c*, *d*, *e*, *f*, 6, *and back to A*, show the apparent places on the straight line at the *same equal intervals* during one complete swing.

f. The apparent motion of the pendulum bob, back and forth, in the path *A*6 is an illustration of what is called *simple harmonic motion.* It is an accelerated motion to and fro, in a straight line. The acceleration is alternately positive and negative (§ 55, *c*).

111. The *time* between two successive passages of the vibrating body through any point in the same direction, is the *period.*

The *distance* from the point of rest to either end of the swing is the *amplitude.*

The number of complete vibrations in a second is the *vibration rate* or *frequency.*

If we divide the period of a simple harmonic motion into any number of equal intervals, each one of these fractional parts is a *phase*.

We can represent this division by drawing a circle whose radius is equal to the amplitude, dividing the circumference into equal parts, and joining corresponding points by lines at right angles to the line of swing. The pendulum then completes one phase as it passes each of these lines.

Thus in Fig. 134 the time to go $A \rightarrow 6 \rightarrow A$ is divided into 12 equal intervals. We count these from *d*, or the middle point of the swing. When the body is at *e*, and going to the right, its phase is $\frac{1}{12}$; at 6 its phase is $\frac{3}{12}$; at *c*, going to the left, it is $\frac{7}{12}$. If the phase is $\frac{11}{12}$, the body is at *c*, going to the right, because, if you count twelfths, beginning at *d* and following the swing to the right, and back and forth, *c* is found to be the eleventh point. Thus the phase describes both the *place* and the *direction* of a body which is in simple harmonic motion.

112. **The Transmission of a Simple Harmonic Motion.** — *a.* If a piece of soft rope, such as clothesline, about 2 m. long, lying straight on a table or floor, be moved at one end trans-

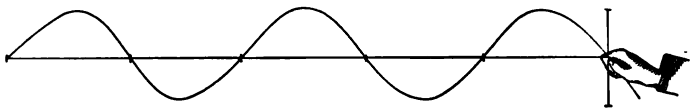


Fig. 135.

versely (§ 110, *e*) with the hand, back and forth, the rope will quickly be thrown into a series of curved forms (Fig. 135). Try it. You should see that the motion of the rope begins at the hand and runs to the other end; that each part of the rope in succession executes a transverse simple harmonic motion like that of the hand. Compare this with the vibration of the cord described in § 110, *d*.

b. A diagram of the facts will show just how the motion is

transmitted by the rope. In Fig. 136, *dd* represents the rope lying straight, *A* 6 the path of the hand in its simple harmonic motion, and *b*, *c*, *d*, etc., its phases in twelfths of a period. As the hand swings, the disturbance of the rope goes along its length, and the dots *h*, *i*, *j*, etc., show how far the motion extends while the hand passes from phase to phase. Let the hand start from *d* toward 6. When the end of the rope, *d*, reaches *e*, *h* is just ready to start. When *d* is at *f*, *h* is on the line *ee*, and *i* is just ready to start. When *d* is at 6, *h* is on line *ff*, *i* on line *ee*, and *j* is just ready to start. When *d* has returned to *f*, *h* is on line 6, *i* on line *ff*, *j* on line *ee*, and *k* is just ready to start. In this way go on finding the position of the points of the rope, and the progress of the disturbance, until the hand has made a complete vibration. The dotted curve shows the facts at the moment when the hand has made $1\frac{1}{2}$ complete vibrations.

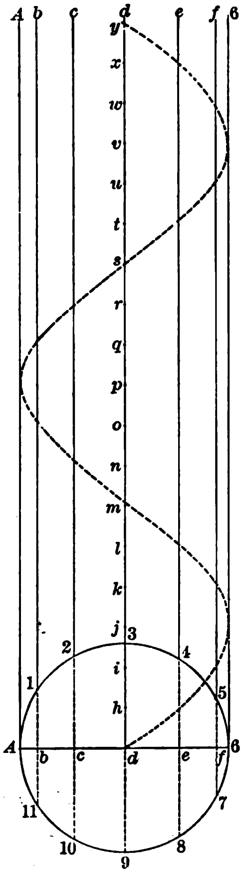


Fig. 136.

c. Mark well this fact: Every one of these points on the rope executes a S. H. M.[1] between the lines *A* and 6, each lagging behind the one before it by just $\frac{1}{12}$ of a period.

S. H. M. may be transmitted through all elastic media in a similar way. The successive portions take energy, each from that before it, and execute a

[1] S. H. M. is the abbreviation for "simple harmonic motion." It should always be read in full. Read it "simple harmonic motion," not "S. H. M."

S. H. M., lagging behind one another by an equal difference of phase.

d. The curved forms of the rope, or, in any case, ***the strained forms of a medium while it is transmitting S. H. M.***, are called ***waves.***

The distance from any particle to the next one which is in the same phase is one *wave length.* Thus from *d* to *s* is a wave length; so is the distance *ht*, or *jv*, or *my*. How many wave lengths are shown in the diagram?

Wave length may be also defined as the distance which the energy travels in a medium while the body which starts it is making one complete vibration. Notice that the diagram shows this.

The *wave rate*, or *wave frequency*, is the number of waves that pass a given point in a unit of time. It is equal to the vibration rate (§ 111) which produces the waves.

113. **Classes of Waves.** — *a.* Waves of all kinds are alike in this: They proceed in straight lines from their starting points, outward through the medium, in all possible directions. But the S. H. M. of the particles of the medium in different kinds of waves differ; in some cases it is at right angles to the direction of the wave, in other cases it is in the same direction as the wave.

b. *RT* (Fig. 137) represents the rope waves described in the previous section (112). Starting from *R*, they flow toward *T*, — the only possible direction for them to go in the linear body. But the S. H. M. of every part is at right angles to that direction, as it is represented by the double-headed arrow. Waves like these, in which the S. H. M. is at right angles to the direction of the waves, are called *transverse waves.* Each wave length includes a crest and a trough.

c. *WT* represents a *section* of water waves, such as are produced by the fall of a water drop or pebble upon the smooth surface of still water. Starting from *W*, the waves roll out-

ward, not only toward *T*, but in all directions over the surface of the water, in concentric circles. But the S. H. M. of every part is in a vertical plane. Hence the water wave is a transverse wave. On closer study, it is found that the particles do not rise and fall in straight lines. Each describes an

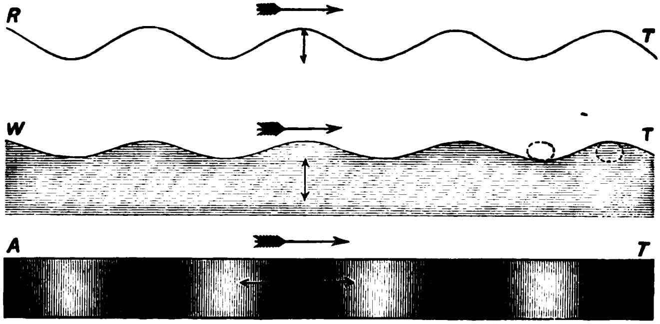


Fig. 137.

ellipse (as shown near *T*); or, if the amplitude is small, a circle, whose diameter is the vertical distance between the top of the crest and the bottom of the furrow. Such waves are called *circular waves.* Each wave length includes an elevation and a depression. It should be noticed that the fall and rise of the water in the wave is due to *gravity*, and the *inertia* of the water.

d. *AT* represents a section of air waves. Starting from *A*, they roll outward toward *T*, and in all other directions through the air. They consist of concentric shells of alternately condensed and rarefied air. But the S. H. M. of the air particles is everywhere in the same direction as the wave itself. Each wave length includes a condensation and a rarefaction. Waves like these, in which the S. H. M. of the particles of the medium is in the same direction as the waves, are called *longitudinal waves.* It should be noticed that the springing back and forth in the air wave is due to the *elasticity* of the air, and not at all to gravity.

114. **The Speed of Waves.** — All waves which, like air waves, are propagated by elasticity, travel with uniform velocity, so long as there is no change in the properties of the medium. The velocity depends on two qualities of the medium; viz., its elasticity and its density.

The velocity of a wave varies directly as the square root of the elasticity of the medium through which it passes, and inversely as the square root of the density.

Sir Isaac Newton demonstrated this law, and letting v stand for speed, e for elasticity, d for density, and supposing each to be measured in its appropriate unit, the law is expressed in symbols by the formula

$$v = \sqrt{\frac{e}{d}}.$$

This formula shows that whatever increases the elasticity, e, of any medium, must increase the speed of waves in it, because the fraction $\frac{e}{d}$ is increased by increasing its numerator. Whatever increases the density, d, of any medium must diminish the speed of waves in it, since the fraction $\frac{e}{d}$ is diminished by increasing the denominator.

This will also be seen from the fact that greater elasticity means a quicker push and recoil, while greater density means more mass, hence longer time to impart the energy.

115. **Studies.** — 1. Cold air is denser and less elastic than warm air under the same barometric pressure; on this account should an air wave travel with greater or less speed in early morning than at midday?

2. If air is confined so that it cannot expand, how will the speed of an air wave be affected when the air is heated?

3. Take the definitions of velocity (§ 10, *c*), wave length, and wave rate (§ 112, *d*), and show that

$$\text{velocity} = \text{wave length} \times \text{wave rate}.$$

4. If the velocity of an air wave is 1120 feet per second, and its wave length is 4 feet, what is its wave rate?

ORIGIN AND TRANSMISSION OF SOUND.

116. **Origin of Sound.** — *a.* Let a small cord be stretched rather tightly (Fig. 133) and plucked at its middle point; its vibrations can be seen, and a sound will be heard. The difference between this cord when sounding and when silent is in its vibrations.

Let a bell be struck; the sound is heard, but no vibrations may be seen. Now suspend a small ivory ball or glass button, by a thread, to rest lightly against the edge of the bell while the sound is heard; the motion and clatter of the ball will declare that the bell is vibrating, although it appears to be at rest. The difference between the bell when sounding and when silent is in its vibrations.

Touch lightly one prong of a tuning fork, a guitar string, or a piano wire, with the suspended ball or with the finger; you will find that, in each case, the difference between the body sounding and silent is in its vibrations.

b. This difference between sounding and silent bodies has been found to exist in so many instances that it is believed to be universal. If so, then the starting point or the *origin of sound is the vibrations of elastic bodies, and hearing is the result of work done in the ear by the energy of these vibrations.*

117. **The Transmission of Sound.** — *a.* The next question is this: How is the sound carried from the vibrating body to the ear?

It has been often shown by experiment that a vacuum cannot transmit sound. Thus let a bell be suspended by a soft cord in the receiver of an air pump (§ 85, *a*), and rung while the air is gradually taken out. The sound, at first distinct, becomes less distinct, until it ceases. Let the air reënter the receiver, and the sound of the bell becomes as distinct as at first. It is inferred from this that the sound is carried by the air.

Bury a music box in cotton inclosed in a box; no sound will be heard. Pass a slender stick through a hole in the cover of the box, and put an empty cigar box against the outer end of the stick. The sound will then be distinctly heard.

Some elastic medium between the vibrating body and the ear is necessary for the transmission of sound. Air is the usual medium, but elastic solids, all liquids, and all gases, transmit sound freely. Substances without much elasticity, such as lead and cloth, have little power to transmit sound.

b. We have seen that a vibrating body imparts S. H. M. to an elastic medium (§ 112, *a*, *b*), and this fact suggests the following explanation of the transmission of sound: *The energy of the vibrations of a sonorous body is carried away by waves in the surrounding medium.*

Take the case of a bell. The energy expended by the hammer is imparted to the bell, and then resides in its vibrating parts. The energy of these vibrations is given to the air, and then resides in the S. H. M. of its particles, which constitutes waves. It passes on from one portion of air to another as the waves advance. If an ear is in their path, the waves roll against it, deliver their energy to that organ, and hearing is the result.

A musical note is heard when a piano key is pressed by the finger; trace the energy from the finger to the ear.

c. Sound is the simple harmonic motion of matter which, if sufficiently energetic, can affect the organ of hearing. This is the definition of sound in physics. It covers both the vibrations of sonorous bodies and the waves in the media which transmit them, but not the sensation in the ear.

118. **The Speed of Sound.** — *a.* It is well known that lightning and thunder are produced at the same moment, and yet the flash is seen before the thunder is heard. The discharge of a cannon in the distance can be both seen and heard, but the hearing lags behind the sight. The blow of a hammer at

a certain distance may be heard as if it were produced by the upward stroke against the air after the blow. Such facts show that sound is not transmitted instantaneously.

b. Efforts to find the speed of sound with precision began in 1738, and have since been made repeatedly. The following method of experiment has been generally adopted: The distance between two stations is measured with great care. A sound and a flash of light are made at the same instant at one station, and observers at the other station carefully record the interval of time between the arrivals of the flash and the report. The time required for the light to make the journey is practically zero. Hence the time between flash and report is that required by the sound to make the journey. The velocity is then computed in the usual way (§ 10, *e*).

c. In the experiments made in Holland in 1822 the two stations were about nine miles apart. A cannon was placed at each station, and the two were fired at the same moment. Each party of observers measured the time between the flash and the report of the cannon at the other station. The sound was sent both ways in order to eliminate the effect of the wind by taking the average of the results.

But there are other sources of error in the experiment. The temperature of the air affects its density, and therefore affects the speed of the sound (§ 114). Damp air is less dense than dry air, and you can explain how the amount of moisture in the air affects the speed of sound. The eye and the ear are not equally quick in announcing the arrival of flash and report.

When these sources of error have been taken into account, the final results of the best experiments show that *the speed of sound in air at* 0° *C. is* 332 *m., or about* 1090 *feet, per second.* For every degree above 0° C., .6 meters, or about 2 feet, must be added. The velocity of sound is independent of barometric pressure, since pressure changes *d* and *e* (§ 114) in the same ratio.

Example. — One day, when the temperature was 30° C., I counted 6 seconds between a lightning flash and the thunder; how far away did the lightning occur?

d. Gases differ in density, but not in elasticity so long as temperature and pressure are the same. Hence the speed of sound in other gases may be computed from that in air according to the law (§ 114). Thus the density of oxygen is 1.1 times that of air. Hence sound travels in oxygen at the rate of $332 \div \sqrt{1.1} = 317.5$, meters per second.

e. The speed of sound in water was measured in 1826 in the following way: Two boats were moored 13,500 m. apart on the Swiss lake, Geneva. One carried a large bell which was rung under water by means of a lever, and this lever ignited a little gunpowder in the air above at the same instant. In the other boat an observer, holding an ear trumpet with its mouth under water, noted the time between seeing the flash and hearing the stroke. The speed was found to be 1435 m. per second at 8.1° C. In other liquids the speed differs according to the general law.

f. The speed of sound in solids is also much greater than in air. Thus in iron at 0° C. it is 5127 m., in lead 1228 m., and in pine wood it is 3322 m. per second.

119. **Studies.** — 1. The speed of a rifle bullet is about 1330 feet per second; which will reach a deer first, the report of the rifle or a well-aimed bullet, when the temperature of the air is 80° F.?

2. There is a reason why sound should travel faster on the summits of high mountains than at their bases; what is it? There is also a reason why it should not; what is it?

3. If a tube connects the distant parts of a large building, words spoken into one end can be distinctly heard at the other. Tubes used in this way are called *speaking tubes.* Explain the transmission of the voice. Can you give the reason why the sound is louder than if made in the open air?

120. **The Reflection of Waves.** — *a.* We have seen that a wave goes in straight lines in all directions from its starting point. We are now to see what happens when it meets an obstacle.

Experiment 73. — *Object.* To study reflection by means of water waves, and to represent the observed facts by diagram. (To become acquainted with terms and definitions.)

1. Cover the bottom of a white porcelain plate with water. Let a single drop fall upon the surface at the center, and watch the waves that roll away to the edge of the plate and then back to their starting point. Disturb the water at some point on one side of the center, and see the waves return from the edge of the plate to a point just as far on the opposite side of the center.

In a similar way waves of all kinds are turned back, or, as it is called, *reflected*, when they encounter a medium whose density is not the same as that of the medium in which they are going.

2. In order to make a more careful study of reflection, repeat the experiment, watch the motion of the water intently, and diagram what you see as follows:

Represent the edge of the water in the plate by a circle. Choose two points, one below the center to represent the starting point, and one just as far above to represent the returning point of the waves. Represent the direction of one particular point in the wave by a straight line from the starting point to the circumference, and the direction of the same point in the returning wave by a line back to the returning point.

b. The experiment and diagram illustrate the following definitions: Waves going toward the reflecting surface are *incident waves.* Waves returning from the reflecting surface are *reflected waves.*

The point on the reflecting surface where any point on the front of an incident wave touches it is the *point of incidence.*

Draw from the center of the circle in the diagram, made as described above, a dotted line to the point of incidence. This radius is perpendicular to the circumference, and the angle between the normal to the reflecting surface (this dotted line) and the direction of the incident wave is called the *angle of incidence.* The angle between the normal and the direction of the reflected wave is called the *angle of reflection.*

c. The experiment and diagram just made illustrate also the following law of reflection:

The angles of incidence and reflection are equal and in the same plane.

121. **Reflection of Sound.** — *a.* If hearing is due to the energy of sound waves, how is it affected by their reflection? This question is answered by a study of the *echo*.

One may hear a syllable of his own voice thrown back to him by a wall, if he stands far enough away and in a line which is normal to the surface of the wall. And he may hear any other sound, if the air waves from its source go obliquely against the wall, and if his ear is far enough away in the path of the reflected waves. To explain this fact, let S (Fig. 138) represent the source of a sound, i represent the point of incidence on the wall, E represent the ear, which may receive the sound directly from S, and also its echo, which is the sound reflected from the wall at i according to the law (§ 120, *c*). The echo has farther to go and is heard later.

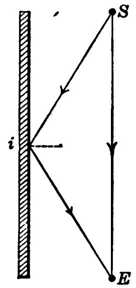


Fig. 138.

b. How far away must the reflecting surface be? The ear holds the sensation of sound about $\frac{1}{10}$ of a second after it is made; hence one hears his own voice for $\frac{1}{10}$ of a second after he has spoken.

The sound must take a little more than $\frac{1}{10}$ of a second to go to the wall and back, in order that the echo of a single syllable may be heard by the speaker as a separate sound. But in $\frac{1}{10}$ of a second, sound goes *about* 112 feet; hence the wall must be at least 56 feet away. In general, the distance from the source of the sound, by way of the reflecting surface, must be at least 112 feet greater than the direct line from the source to the ear. If the difference in paths is less than that, the sound and its echo are blended.

Try the reflection of sound as follows: Place a smooth board edgewise on the table. Lay a long piece of tubing in a line Si, and have a watch held against its open end, S. Lay another piece of tubing in a line iE, and place the ear at the open end, E. Vary the angles.

122. **The Length of a Sound Wave.** — *a.* A simple continuous sound, like that of a tuning fork, consists of a series of air waves following each other rapidly at regular intervals of time. These waves consist of alternate condensations and rarefactions of the air. The distance between the like phases (§ 111) of two consecutive waves is called the *wave length* of the sound. It may be measured from the beginning of one condensation to the beginning of the next, or from the middle of one condensation to the middle of the next, or from any other point in one condensation or rarefaction to the corresponding point in the next.

b. Suppose a tuning fork of 435 vibrations per second to remain vibrating just one second. In that time 435 waves will have left the fork. At 0° C. the sound travels with a speed of 332 m. per second (§ 118, *c*). Then the first one of the 435 waves will be 332 m. from the fork at the end of a second, and there will be 435 waves in the 332 m. The length of one wave, in this case, is 33,200 ÷ 435, or about 76.32, cm. In all cases:

$$\text{Wave length} = \frac{\text{velocity of sound}}{\text{vibration rate of sounding body}}.$$

Example. — If the "middle C" wire of a piano vibrate at the rate of 258.6 per second, what would be the wave length of the sound it emits at a temperature of 18° C.?

SYMPATHETIC VIBRATIONS AND RESONANCE.

123. **Sympathetic and Forced Vibrations.** — *a.* Under certain conditions vibrations may be communicated to a body by well-timed repetitions of feeble impulses, instead of by a single energetic push or pull.

Experiment 74. — *Object.* To set a heavy pendulum vibrating with large amplitude by well-timed, feeble impulses.

Attach a fine silk thread to a heavy pendulum (Fig. 22). Grasp the other end of the thread and pull gently enough not to break it, and then

relax. Do this repeatedly, timing the hand so that the pulls occur only when the pendulum is beginning its swing toward the hand.

Try again by timing the pulls irregularly.

The vibration rate of the hand must be the same as that of the pendulum.

b. A body is moved through a very small arc by the energy of one of the feeble impulses, but it returns just in time to receive the next, which makes the second swing greater than the first. At the end of the second swing another impulse is added, and, in this way, the energy of successive impulses is accumulated, thus increasing the amplitude.

But in case the impulses are not timed to agree with the vibration rate of the body, the energy of one is received by the body sometimes at one end of its arc and sometimes at other points, thus promoting the swing at one time and opposing it at another.

The vibrations imparted to one body by another having the same vibration rate are called *sympathetic vibrations.*

c. The law of sympathetic vibrations can be stated as follows: *The vibrations of one body are freely imparted to another on condition that the vibration rates of the two are equal.*

124. **Reënforcement of Sound.** — *a.* If a vibrating tuning fork is held in the hand, its sound is scarcely audible, but let its stem be firmly pressed upon the table, and its sound is heard distinctly. The sound of the fork is reënforced by the sympathetic vibrations of the table.

b. The explanation is as follows: When a small mass of air vibrates, the energy of the condensations and rarefactions may not be able to affect the ear. This is the case with the vibrating tuning fork. Its prongs, having small areas, produce feeble air waves. But when its stem is pressed upon the table, it forces vibrations in the table top, and the air waves produced by the vibrations in the table are added to those of the fork. In this way air waves are produced with energy enough to affect the ear.

But the vibration rate of the table is not the same as that of the fork whose sound it reënforces. This would seem to conflict with the law (§ 123, *c*). There is, however, no real conflict. The table does not vibrate as a whole; it vibrates in small portions, each of which has the same rate as the fork.

c. Sympathetic vibrations play a very important part in the production of sound by musical instruments. Piano wires, for example, are stretched over a sounding board which reënforces their sounds. Otherwise they would be almost inaudible.

125. **Resonance.** — *a.* The reënforcement of a sound by the sympathetic vibrations it produces in a neighboring body is called *resonance,* and a body which has been carefully constructed to have the same rate as another whose sound it is intended to reënforce, is called a *resonator.*

b. The sound of a tuning fork may be strengthened by an air column which has the right size to have the same vibration rate. This is shown by the following experiment:

Experiment 75. — Hold the prongs of a vibrating fork with their plane vertical (Fig. 139) over the mouth of a cylindrical jar about two inches in diameter, while you pour water in slowly, letting it run down the wall so that it will not splash. As the air column becomes shorter, the sound becomes louder, until a certain length is reached. After this the sound grows weaker as the column shortens.

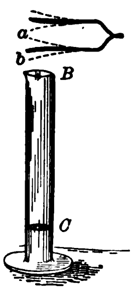


Fig. 139.

c. We explain the action in this way. When the prong of the fork swings from *a* to *b*, it condenses the air in the jar. When it swings back, from *b* to *a*, it condenses the air outside. The condensation in the jar goes down to the bottom, is reflected (§ 121), and returns to the mouth. If the distance *BC* is just right, the condensation will go to the bottom and back while the prong is going from *a* to *b*, and be just in time to combine with the condensation produced outside by the prong as it goes from *b* to *a*.

In the same way, a rarefaction goes to the bottom and back

to the mouth of the jar, while the prong is going from *b* to *a*, and arrives just in time to combine with the rarefaction outside, produced by the prong in its motion from *a* to *b*. Thus the condensations and rarefactions of the air column reënforce those produced outside by the fork, and so strengthen the sound.

But when the air column is a little longer or shorter, the reflected waves do not reach the mouth of the jar at the right time to combine with those produced outside by the fork. Therefore the sound is not strengthened.

126. **Relation between the Lengths of the Air Column and the Sound Wave it reënforces.** — *a.* This relation may be seen as follows: The motion of the prong of the fork from *a* to *b* is a single vibration (§ 69, *b*). The condensation produced travels from *B* to *C* and back, or twice the length of the air column, during that half vibration. Hence the air column is one half the length of a condensation, and therefore one fourth the length of a sound wave.

In general: *A resonant air column, with one end fixed,* as by the bottom of a jar or the end of a closed tube, *is one fourth the length of the sound wave which it reënforces.*

b. It is found by experiment that the length of the air column is not exactly what this principle requires. The diameter of the tube makes some difference. If the tube is wider, the resonant air column is shorter. So that in the case of cylindrical tubes, two fifths of the diameter must be added to the length to obtain the one-fourth length of the sound wave.

c. We are now prepared to find the wave length of a sound; for, if we can measure the length, l, and diameter, d, of its resonant air column, we shall have wave length $= 4\,(l + \frac{2}{5}\,d)$.

Experiment 76. — *Object.* To find the wave length of the sound of a tuning fork by the resonance of a closed tube.

If an open tube be inserted in a jar of water (Fig. 140), the length of the air column within may be varied at will by lowering or raising it. The tube may be of glass or metal, about 50 cm. long, and about 4 cm.

in diameter. A 20-inch length of large size "speaking tube" is suitable.

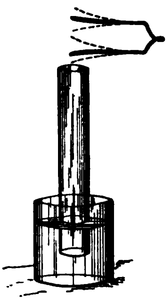


Fig. 140.

The vibrating prongs of the fork should be held in a vertical plane, and as near the end of the tube as may be without touching. A *c* fork, whose vibration rate is 128, is suitable.

The variation in the sound should be observed both when the tube is lowered and when it is raised, until the point of greatest loudness is found with certainty. The length of the air column should then be measured to the nearest .1 cm. This measurement is made easier if a meter scale is bound alongside the tube. The observations should be repeated several times.

Note the measurements as follows:

Diameter of the tube	—— cm.
First measurement of length of air column . .	—— cm.
Second measurement of length of air column . .	—— cm.
Third measurement of length of air column . .	—— cm.
Temperature of the room	—— C.

Compute the mean of the observed lengths, and correct it for diameter. Then compute the wave length of the sound.

d. We have seen (§ 118, *c*) that the speed of sound in air at 0° C. is 332 m. per second, and increases about .6 m. for each degree of rise of temperature. Now remembering (§ 122, *b*) that

$$\frac{\text{Velocity}}{\text{Wave length}} = \text{vibration rate,}$$

we may find the rate of the fork, or the *wave frequency* of a sound (§ 112, *c*), if its wave length is known. What is the computed frequency of the fork used in the foregoing experiment?

e. The vibration frequency of the fork may be marked upon its stem. If so, assume it to be correct, and compute the speed of sound in the air at the time the experiment was made.

127. **Relation between Wave Length and the Length of an Open Tube.**—*a.* The air in a tube open at both ends will reënforce the sound of a tuning fork, but the tube must be longer than

if it were closed at one end. In fact, it must be twice as long.

Experiment 77. — *Object.* To find the relation between the length of an open tube and the wave length of the sound which it reënforces.

Fix the tube used in the preceding experiment in a horizontal position (Fig. 141). Roll a sheet of paper upon it just so tightly that it may slide with little friction, and bind it with a few turns of small twine. The length of the tube may be varied at will by sliding this paper cylinder. Hold the vibrating fork used in the preceding experiment, close to the mouth of the tube, and observe the variation in the sound as you gradually lengthen the tube. Continue to vary the length until the maximum loudness is obtained with certainty. Then measure the length of the tube accurately, and compare it with the length of the closed tube which reënforced the same sound (§ 125, *b*). It should be twice as long. But the same sound has the same wave length; hence the length of the tube and the air column within is one-half the wave length of the sound.

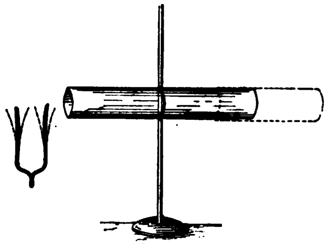


Fig. 141.

b. The explanation of the difference between this and the former case is not hard to find. The condensation which is reflected from the end of a closed tube passes out into open air at the end of an open tube, and a rarefaction is reflected instead; so that an open tube must be the length of a whole condensation. The air within the tube is alternately the full length of a condensation and a rarefaction, and hence one half the wave length of the sound.

In general, *an open tube is one half the wave length of the sound which it emits or reënforces.*

MUSICAL SOUNDS.

128. Musical Sounds. — *a.* A musical sound is one whose effect in the ear is continuous and agreeable. It consists of simple harmonic motions, which reach the ear in rapid succes-

sion and with regularity. The waves enter the ear so rapidly that no interval of time can be detected between them; this makes the hearing continuous. They are periodic; this makes the hearing agreeable.

b. Musical sounds differ in *pitch;* this difference enables us to distinguish sounds as high or low. They also differ in *intensity;* this difference enables us to distinguish sounds as loud or soft. And they differ in *quality* or *timbre;* this difference enables us to distinguish sounds which are alike in pitch and intensity, when made by different instruments.

Experiment 78. — *Object.* To discover, if possible, by studying the vibrations of cords, what it is that the ear recognizes as pitch and intensity of sound.

Two blocks, each with a screw-eye, may be clamped upon the ends, or along the edge, of a table, about a meter apart, more or less (Fig. 142). One end of a slender cord may be fixed to one screw-eye, and the other end may be passed through the other screw-eye. By pulling this free end, the tension of the cord may be varied.

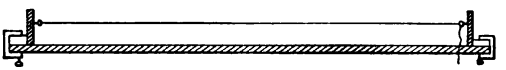


Fig. 142.

1. Let the tension of the cord be slight, so that while the vibrations are visible no sound is heard. The cord is vibrated by plucking its middle portion. Increase the tension; pluck the cord about as forcibly as before; watch for any visible change in the rapidity of the vibrations, and also for any sound that may be produced. Increase the tension more and more, and compare the rapidities, and also the sounds.

How does the ear recognize the higher rates of vibration? Are there vibrations too slow to be heard at all?

2. Stretch the cord tightly, and fasten the free end so that the tension will be steady. Pluck the cord gently; observe the amplitude of its vibrations, and also the sound produced. Then pluck it with greater energy, and again observe the amplitude and the sound; you should discover and note the changes in both. Repeat, varying the amplitude by varying the energy with which the cord is plucked.

How does the ear recognize the greater amplitudes of vibration?

129. **Pitch.** — *a.* If two vibrating bodies have the same vibration rates, their sounds have the same pitch, however much they may differ in other respects. When the number of vibrations per second is great, the pitch is high, or acute; when small, the pitch is low, or grave. A musical sound of definite pitch is called a *tone.*

b. The music of civilized nations is based upon a series of musical sounds, chosen out of the vast number of possible tones. Starting from any pitch, and taking them in their order of pitch, twelve different tones are used. The thirteenth is very much like the first in all respects except pitch, and is called its *octave.* By suitable choice out of these tones various series are formed called *scales.* The most important scale in music is that called the *diatonic major scale.* It selects seven out of the twelve tones, the eighth tone of the scale being the octave of the first. The first, or lowest, tone is called the *fundamental,* or *keynote,* of the scale.

c. The tones in the scale are designated by letters. In the case of that major scale whose keynote is *C,* the letters are as follows: *C, D, E, F, G, A, B.* The octave is named *C* again, and serves as keynote of the scale of tones above it. In written music they are represented by symbols, called *notes* (𝅗𝅥 ♩ ♪), and their relative pitches are shown to the eye by writing these symbols upon the *staff,* which consists of horizontal lines with the intervening spaces. A symbol on a higher line or space represents a note of higher pitch. Thus:

d. By the use of the capital letters, small letters, and letters with dashes or primes attached, the actual pitches of the tones in the repetitions of the scale are distinguished.

In the case of other scales, or of the major scale with another keynote than *C*, one or more of the five tones omitted from the series displayed above must be added, or substituted for some of the tones given. These omitted tones, when needed, find their places on the staff by means of signs called *flats* (♭) or *sharps* (♯) used in connection with the notes.

e. The actual pitch, or vibration frequency, of the fundamental of the scale is not fixed. It may be higher or lower, but the difference in pitch of the successive tones is always the same.

The difference in pitch of two sounds is called an *interval*. The value of an interval is measured by the ratio of the vibration frequencies of the two sounds. It is found by dividing the higher frequency by the lower. Thus if one piano wire vibrates 256 times per second, and another 320, the difference in pitch, or interval, of the two sounds if $\frac{320}{256}$, or $\frac{5}{4}$.

f. Now the tones of the major scale do not differ in pitch uniformly. If we take the frequency of the fundamental as 1, then the ratios of the others to it are as follows:

c	*d*	*e*	*f*	*g*	*a*	*b*	*c′*
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2.

So that whatever pitch is assigned to *c*, that of *d* will be $\frac{9}{8}$ of it, of *e* $\frac{5}{4}$ of it, and so on. For example: If a sound whose wave frequency is 128 per second be taken as the fundamental, *c*, then the wave frequency of *d* is $\frac{9}{8} \times 128$, or 144 per second. The student should finish this illustration by computing the wave frequency of each note of the entire series.

The octave of one scale is the fundamental of the next higher, and the same series of intervals are repeated. Thus for tones following *c′* we have $2 \times \frac{9}{8}$, $2 \times \frac{5}{4}$, $2 \times \frac{4}{3}$, or $\frac{18}{8}$, $\frac{10}{4}$, $\frac{8}{3}$, and so on. These ratios are the frequencies of the tones compared with that of the lowest fundamental, *c*.

Instead of taking the interval between the fundamental and each of the other tones, we may find the interval between each and the one next higher. Thus the interval between *c* and *d* is $\frac{9}{8} \div 1$, or $\frac{9}{8}$; between *d* and *e*, $\frac{5}{4} \div \frac{9}{8}$, or $\frac{10}{9}$. Each fraction divided by the one before it gives the interval between the corresponding tones. In this way you should compute the seven intervals of the scale, from the fundamental, *c*, up to the octave, *c'*, and find them to be as follows:

$$c \ldots d \ldots e \ldots f \ldots g \ldots a \ldots b \ldots c'$$

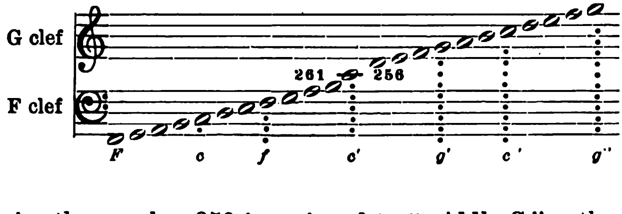
$$\tfrac{9}{8}, \quad \tfrac{10}{9}, \quad \tfrac{16}{15}, \quad \tfrac{9}{8}, \quad \tfrac{10}{9}, \quad \tfrac{9}{8}, \quad \tfrac{16}{15}.$$

By so doing you discover that there are only three different values.

These three intervals are named as follows: The $\frac{9}{8}$ is called a *major step*, the $\frac{10}{9}$ a *minor step*, and the $\frac{16}{15}$ a *major half step*.

Other important intervals in the scale are the *major third* (*c* . . . *e*), the numerical value of which is $\frac{5}{4}$; the *fourth* (*c* . . . *f*), the value of which is $\frac{4}{3}$; the *fifth* (*c* . . . *g*), the value of which is $\frac{3}{2}$; and the *minor third* (*a* . . . *c'*), whose value is $\frac{6}{5}$.

g. While the number of vibrations per second which shall constitute a fundamental is purely arbitrary, yet for practical purposes certain standards have been adopted. Thus, *in*



physics, the number 256 is assigned to "middle C,"—the tone whose note is written on the line between the G and F "clefs;" it is the *c'* of the preceding paragraph, and of the

diagram above. An international commission of musicians have recommended a "standard pitch," fixing the a' at 435. This is called the *international pitch*, and is that to which most musical instruments are now tuned. According to this, the frequency of c' is 261 ($435 \times \frac{3}{5}$). The student will do well to compute the numbers for the tones of the natural scale on each of these two standards. Thus the actual rates of vibration of piano wires, or the vocal cords of a singer, when these particular sounds are made to natural scale, become known.

h. The above ratios (*f*) are theoretically correct. In musical practice, however, they are slightly modified to secure uniformity in the intervals. The octave is divided into twelve equal intervals, called *half-steps*. The *step* is equal to two half-steps; the *minor third*, three; the *major third*, four; the *fifth*, seven; and so on. The system thus adopted is called *equal temperament*. The effects of equal temperament are not as beautiful as with the ratios given (§ 130, *b*), but the advantages to music in other respects are thought to outweigh the loss in purity of interval. The half-step ratio is 1.05946.

i. The lowest tone useful in music has a rate of about 32 per second, and the highest about 4000. To include the large number of musical sounds between these limits, the scale is repeated over and over (*f*). You may learn how many repetitions of the scale are needed by finding how many times you must multiply by 2 in order to raise 32 to 4000 +, since the vibration frequency of each octave is twice that of its fundamental.

j. The limits of *audible* sounds are very much wider than those of sounds which are *practically useful* in music. Human ears, however, are not equally sensitive. Many people have heard the acute cry of the bat and the creak of the cricket, but others never have, because these sounds transcend the sensibility of their ears. The limits of hearing, therefore, cannot be definitely stated, but the extreme range of audible sounds

may be put as at least 16 vibrations per second for the lowest to about 40,000 for the highest.

130. **Chords.** — *a.* A smooth, pleasing effect in the ear, produced by two or more sounds combined, is called *harmony*, and the sounds themselves constitute a *chord*. An unpleasant, jarring effect in the ear, produced by two or more sounds combined, is called *discord*.

b. Whether the effect of two sounds combined shall be pleasing to the ear or not, is found to depend on the ratio of their wave frequencies. If that ratio is a simple one, the effect is harmony; if the ratio is more and more complex, the harmony degenerates into discord. The following facts illustrate this principle:

In the unison . .	ratio 1 : 1, the sounds blend perfectly.
In the octave . .	ratio 2 : 1, the roughness is very slight.
In the fifth . . .	ratio 3 : 2, the roughness is greater.
In the fourth . .	ratio 4 : 3, the roughness is still greater.
In the major third .	ratio 5 : 4, the roughness is still greater.
In the minor third .	ratio 6 : 5, the roughness is quite marked.

When sounds whose wave frequencies are more nearly equal than those of the minor third are combined, the resultant sound in the lower octaves is too harsh to be agreeable.

c. According to Helmholtz, the dissonance of two sounds is due to beats (§ 136, *c*). When the wave frequencies are nearly equal, the beats are so rapid that they cannot be heard separately, but produce a continuous jar which is unpleasant to the ear.

131. **The Transverse Vibrations of Strings.** — *a.* An instrument for the study of the vibration of strings is called a *sonometer*. This instrument, which has been known since the days of the ancient Greeks, consists of a narrow wooden box, usually about a meter in length. Over the top of this resonant case one or more metal strings may be stretched.

b. Mersenne, by means of such an instrument, found that the vibration frequency of a string depends on three things, its length, its tension, and its mass (the mass of a unit length), and proceeded to discover the following laws:

1. *The vibration frequencies of strings whose masses are equal, and which are stretched with the same tension, vary inversely as their lengths.*

Thus if two pieces cut from the same wire, one 80 cm., the other 40 cm., long, are stretched equally, the shorter will vibrate at a rate twice as great as the other. In every case, if L and R stand for the length and rate of one string, and l and r for the length and rate of another of equal mass and tension,

$$R : r :: l : L. \tag{1}$$

2. *The vibration frequencies of two strings whose masses and lengths are equal, vary directly as the square roots of their tensions.*

Thus if two strings have equal masses and equal lengths, and one of them is stretched with a tension 4 times that of the other, it will vibrate twice as fast. Other things being equal, the vibration frequencies of two wires, one stretched by the weight of 25 pounds, the other by the weight of 36 pounds, are as $\sqrt{25} : \sqrt{36}$, or as $5 : 6$. In any case, if T and R stand for the tension and rate of one, and t and r for the tension and rate of another with an equal length and mass,

$$R : r :: \sqrt{T} : \sqrt{t}. \tag{2}$$

3. *The vibration frequencies of two strings whose lengths and tensions are equal, vary inversely as the square roots of their masses.*

Thus if the mass of one string is 9 times the mass of another of equal length and tension, it will vibrate $\frac{1}{3}$ as many times per second. Other things being equal, the vibration frequen-

cies of two wires whose masses are as $9:16$ are as $\sqrt{16}:\sqrt{9}$, or as $4:3$. In every case, if M and R stand for the mass and rate of one string, and m and r for the mass and rate of another with an equal length and tension,

$$R:r::\sqrt{m}:\sqrt{M}. \tag{3}$$

c. These laws are applied in the construction and tuning of stringed instruments of music, such as the pianoforte, violin, and harp. The pitch of each tone is secured by using a string of appropriate length and mass, and then straining it with just the right tension.

132. Experimental Study of String Vibrations. — The top of a pine table is a very good substitute for the resonant box of a sonometer. Wires may be stretched over it as shown in Fig. 143. The two blocks

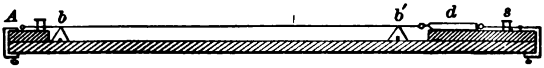


Fig. 143.

used in experiments on tenacity (Fig. 46) are clamped upon the ends or the edge of the table. The wire (brass, No. 24), with one end fastened in the screw-eye at A, is wound two or three times around the adjacent spool, and the other end is fastened to the hook of a spring balance, d. A piece of strong twine, tied into the ring of d, is passed around the spool s, and serves to fix the balance when the wire is properly strained. Two bridges, b and b', are placed under the wire near its ends, as shown. The balance should lie flat upon its back, supported by a block, so that the wire is bent down a little over the edge of b'.

The *length* of the string is measured from b to b', or to a third bridge which may be moved under the string between these points to vary the length of the vibrating part at pleasure. The *tension* of the string is secured by pulling the twine, and it is measured by the balance, d. The *mass* is varied by using strings of different sizes or of different materials. Two tuning forks are needed with which to identify the sounds produced, one a c' fork $= 256$, the other a c fork $= 128$, vibrations per second.

To succeed in the experimental study one must be able to judge correctly whether two sounds are in unison, and must make the measurements with care.

Experiment 79. — *Object.* To verify the relation between the vibration rates and lengths, of strings whose tensions and masses are equal.

A single wire of No. 24 spring brass may be used. Let the apparatus be set up as described above, with the distance between b and b' about 60 cm. Push the hook end of the balance with the left hand while you pull the twine around the spool, s, until the index stands at, say, 8 pounds, and then fasten it firmly. Pluck the wire near its middle point, and compare its sound with that of the c fork. If it is higher than c, slacken the twine a little; if lower, tighten the twine, and perhaps put a third bridge near b', and shorten the vibrating part until the wire is in unison with the fork. One ear should be placed near the wire, while the vibrating fork is held near the other. Beats may be heard when the two sounds are near unison; they will become slower and finally disappear when the unison is obtained.

Note the vibration rate of the wire; it is the same as that of the fork (§ 129, *a*). Measure the length of the vibrating part of the string. Several trials should be made, and the average taken.

Now, *leaving the tension unchanged*, move the third bridge toward b, until the sound of the wire is in unison with the c' fork. Note the vibration rate of the string, and its length, finding an average as before.

By comparing the rates and average lengths (Appendix II.) you should be able to state the relation between the vibration rates and the lengths of stretched strings. Compare your conclusion with the law (§ 131, *b*, 1).

Experiment 80. — *Object.* To verify the relation between the vibration rates and the tensions of strings whose lengths and masses are equal.

The tension of the string is measured by the balance, d. It is the weight of as many pounds or grams as the scale indicates.

Make the tension of the wire such that the scale reading is 2 or 3 pounds. Place the third bridge under the wire, and move it until the sound of the wire is in unison with the c fork. Then, without permitting the bridges to be moved, increase the tension until the sound is in unison with the c' fork. Note the vibration rates and the corresponding tensions, finding an average in each case. You should then be able to state the relation between the vibration rates and the tensions of stretched strings. Compare your conclusion with the law (§ 131, *b*, 2).

Experiment 81. — *Object.* To verify the relation between the vibration rates and the masses of strings whose lengths and tensions are equal.

Cut equal lengths of Nos. 24 and 27 spring brass wire. Find their masses by the balance, and compute the masses per meter, M and m.[1]

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[1] The mass of any length of No. 24 spring brass wire is *very nearly* twice that of the same length of No. 27.

Choose a tension, say 10 pounds, and find, by moving the bridge, what length, L, of No. 24, will give a sound in unison with the c fork = 128. Substitute a wire No. 27, stretching it with an equal tension, and find what length, l, will yield a sound in unison with the c' fork = 256. From the rate of the l cm. of No. 27 compute the rate, x, of 1 cm. of the same wire; $x : 256 :: l : L$ (§ 131, b, 1).

Now, having the vibration rates and the masses of the wires, which are equal in length as well as in tension, compare the two and state the relation. Compare your result with the law (§ 131, b, 3).

133. **Segments and Nodes.** — *a.* A sonorous body generally vibrates in divisions. Fig. 144 represents a stretched string,

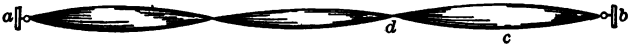


Fig. 144.

ab, which has been plucked at a point *c*, and at the same moment lightly touched at *d*, one third of its length from *b*. It vibrates in three parts as if it consisted of three strings. The vibrating parts of the string are called *segments*. The points of rest, or of little amplitude, as *d*, are called *nodes*, and the points of greatest amplitude, as *c*, are called *antinodes*. Had the string been touched at its middle point, there would have been two segments; at a point one fourth its length from *b*, there would have been four segments.

Experiment 82. — *Object.* To study the production of segments of a vibrating string, by Melde's method.

In Melde's method of producing nodes and segments, the string is vibrated by the prong of a tuning fork to which one end is fixed, while it

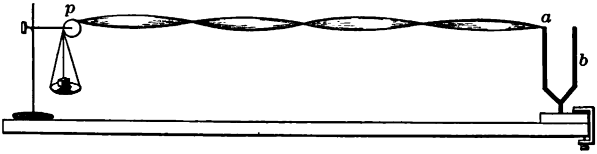


Fig. 145.

is stretched by the weight of a mass hung upon the other end (Fig. 145). Fix the stem of a large c' fork firmly in a block and clamp it to a table.

Make a small loop on each end of a white silk thread about 1 m. long (Cutter's white "buttonhole twist"). Put one loop on the end of one prong of the fork, pass the other over a small pulley, and attach a small scale pan (Experiment 15, Note 2), whose mass you have already found; it should not be more than 5 or 6 grams. Let the plane of the prongs be in line with the string, and make the length *ap* to be 80 cm.

Put box-masses into the pan until they, with the pan, amount to 7 g. Vibrate the fork by drawing a violin bow across the end of the prong *b*, as nearly in the plane of the prongs as may be without touching prong *a*. A little practice will enable you to do this well, and you should then see the string break up into several segments separated by sharply defined nodes.

If the segments do not appear, the tension is far from right; if they appear poorly developed and die out quickly, the tension is nearly, but not quite, right. In every case the masses should be carefully adjusted until the segments are well formed and diminish slowly in amplitude. The number of segments and the corresponding tension should then be noted.

Proceed to obtain smaller numbers of segments by increasing the masses in the pan, and tabulate the results. The following table contains the notes of one experiment. It shows the form of record and the kind of results that may be expected.

Length of Cutter's white buttonhole twist used . . . 80 cm.
Mass of the scale pan . . . . 6.5 g.
Let N stand for the number of segments obtained.
Let m stand for the box-masses used.
Let T stand for tension (represented by the total mass of the scale pan and its contents).

N	m	T	$\sqrt{T}$	$N \times \sqrt{T}$
6	.5 g.	7.0 g.	2.64	15.84
5	3.5 "	10.0 "	3.16	15.80
4	9.4 "	15.9 "	3.98	15.92
3	21.7 "	28.2 "	5.30	15.90
2	52.0 "	58.5 "	7.65	15.30

Columns 4 and 5 are *computed* from the *observed* values. Consider whether the products in column 5 are all so nearly equal that their variations may be fairly attributed to necessary errors in the experiment. If so, we infer that *the number of segments varies inversely as the square*

root of the tension of the string (see conclusion of Experiment 52, or Appendix II.).

For example: 6 : 5 : : 3.16 : 2.64. This is a true proportion, because the product of the extremes equals the product of the means, as shown by the products in the fifth column.

b. Segments vibrate as if they were separate cords. In the case of two segments, each is one half the length of the whole string, and hence its vibration rate is twice as great (§ 131, *b*, 1). If there be three segments, each is one third the length of the string, and its rate is three times as great.

Experiment 83. — *Object.* To obtain audible sounds by the vibration of a string in segments.

Use the apparatus shown in Fig. 143. Stretch the wire, *bb′*, until its sound is in unison with the *c* fork. Then pluck the wire, or draw a violin bow across it, near one end, and at the same instant touch the wire lightly, for a moment only, at its *middle point.* If this is done successfully, the sound will be found to be in unison with the *c′* fork. Pluck or bow the wire again, and touch it lightly for a moment at *one third* its length from *b′*, and listen for a sound still higher. By touching the vibrating wire at one fourth and at one fifth its length from one end, still higher sounds may be obtained.

Explain the production of these higher tones by the law of lengths (§ 131, *b*, 1), applying it to the segments produced by the touch.

c. The tone produced by a body vibrating as a whole (Fig. 133) is its *fundamental.* The tones of higher pitch produced by a body vibrating in parts (Fig. 144) are called *overtones,* or, if they harmonize with the fundamental and with one another, they are called *harmonics.*

134. **Quality or Timbre.** — *a.* Quality has already been defined as that difference in sounds which enables us to distinguish those of different instruments, even when they have the same pitch and loudness. Thus a piano wire, a violin string, or a singer's voice, may yield the same tone, *c′*, and yet it is not difficult to tell from which the sound proceeds, even if in another room. The sound from each source has its own peculiar quality.

b. The quality of a sound is produced by the overtones which blend with the fundamental tone of the sonorous body.

With almost no exceptions the sounds we hear are complex, because, with almost no exceptions, sonorous bodies vibrate as wholes and in segments at the same time. A trained ear can detect several of the harmonics which are blended with the fundamental in the tone of a piano wire. Almost any person can detect one or more. Try it.

According to Helmholtz and Koenig, quality depends on the overtones in three ways:

1. Their number.
2. Their relative loudness.
3. Their phases (§ 111).

INTERFERENCE OF SOUND.

135. **Interference of Waves.** — *a*. Waves, in passing through a medium, are likely to encounter other waves. In the atmosphere, for example, sound waves from many sources must often traverse the same portion of air at the same time. They may be going in the same direction or in opposite directions, or their paths may cross at any angle. The mutual action of two or more systems of waves, in the same direction or in opposite directions, is called *interference*.

b. The interference of water waves may be observed in the following experiment:

Experiment 84. — Put a shallow layer of water into a rectangular pan, such as a sheet-iron baking pan. Lift one end of the pan an inch or two; pause a moment, and then let it down. One set of waves should be transmitted and reflected. Then strike the middle of one side of the pan a sharp blow with the hand, and watch the two sets of waves that meet at the center of the surface. Strike the pan near one corner. Disturb the water by means of falling drops, and in other ways, and watch the two or more sets of waves which are produced. You should see that in every case the encounters of two or more sets of waves stop neither; water transmits any number as freely as one. This is true of all media.

c. A study of the diagrams (Fig. 146) will reveal the *law of interference.* Suppose a wave starts from *A*. It goes in all possible directions, but we show only the path of one point, toward *W*. Suppose the disturbance at *A* to be repeated so that the waves shall not die out. Again, II. represents another wave, with smaller amplitude but the same wave length, starting from *B*. If *A* and *B* are on the same water surface, the two waves will combine at *A*. Crest will be *added* to crest, and trough to trough, forming a single resultant wave, as shown in III. by the curve *A W*. The amplitude of this resultant must be equal to the sum of the amplitudes of the two separate waves.

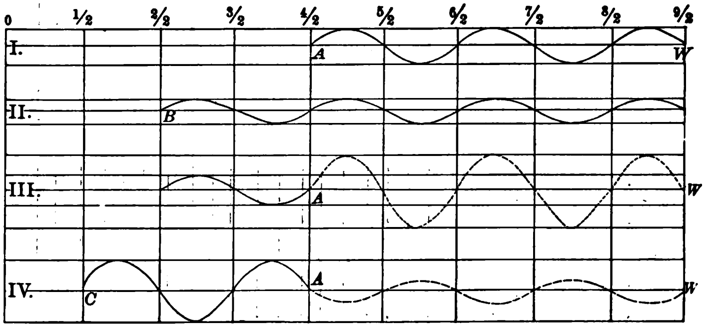


Fig. 146.

Again, suppose the second wave to start from *C*. If *A* and *C* are on the same surface, the two sets of waves will unite at *A*, but the crests of *C* will coincide with the troughs of *A*, and the amplitude of the resultant wave will be equal to the *difference* of the amplitudes of the two, as shown by the wave form *A W*, in IV.

In the first case the resultant is found by adding the amplitudes of the two waves at each point, because the motions of that point, due to the separate waves, are in the same direction. In the second case it is found by subtracting, because

the motions due to the two waves are in opposite directions. But in both cases, it is the *algebraic sum* of the two.

d. In all cases, the following law of interference prevails: *If two or more waves are passing through the same medium, in the same or the opposite direction, they unite to form a single resultant wave. The amplitude at each point is the algebraic sum of the amplitudes of the two separate waves at that point.*

e. For better acquaintance with this law, study the diagrams (Fig. 147). Notice that the waves represented in I. and II. have equal amplitudes, but different lengths. If they were going through the same medium together, they would unite in a wave

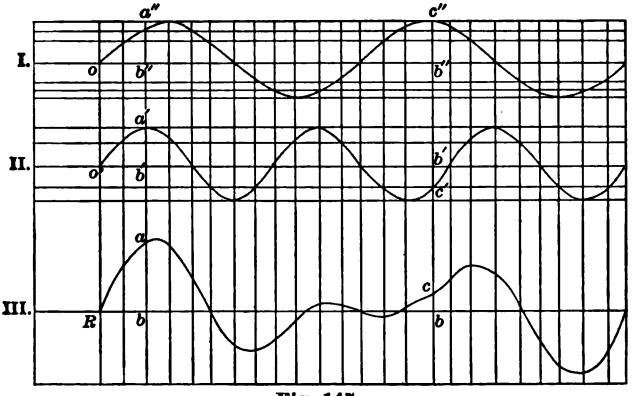


Fig. 147.

whose form is shown in III. Notice that the amplitude at each point in this resultant is the sum or difference of the separate amplitudes, according as that part of the medium is urged in the same or an opposite direction by the separate waves. Thus $ba = b'a' + b''a''$, and $bc = b''c'' - b'c'$.

f. The law applies to waves of all kinds. In air waves you have to think of condensations and rarefactions instead of crests and troughs. Two condensations thrown together produce a greater condensation, as crest with crest produces a resultant higher crest.

136. Interference of Sound. — *a.* If hearing is due to the energy of sound waves, how is it affected by their interference? Study this question as follows:

Get two tuning forks of the same pitch. Strike the end of one prong of each fork on a thin pad of paper or pamphlet lying on the table, and immediately rest the handles of both upon the table or a box. The sounds of the two should be heard as one sound louder than either, perfectly continuous and smooth.

Each of these forks produces its air waves, and the two sets must be of equal wave length because the forks have the same vibration rates. They unite, as shown in Fig. 146, and in the resultant wave (III.) the condensations are all equal, and strike the ear drum with equal energy. Hence the loudness of the sound is uniform.

b. Press a small ball of wax upon the end of a prong of one fork, vibrate the two forks, and rest them on the table as before. Try larger and smaller pieces of wax, noticing the varying loudness of the sound in each case. Periodical bursts of sound, with intervals of comparative silence, follow more or less rapidly as the load of wax is changed.

The effect of the load is to reduce the vibration rate of the fork. The slower vibrations produce longer air waves. These blend with the shorter waves of the other fork, as shown in Fig. 147, and in the resultant waves (III.) the condensations are unequal. The greater condensations follow one another at intervals, with lesser condensations intervening, and the blows of these unequal condensations upon the ear drum produce the unequal loudness of the sound. Try the following experiment:

Hold a vibrating tuning fork near the ear, and turn it slowly around its axis. A point will be found at which the sound will be extinguished.

Repeat Experiment 75, and, having found the proper length of the air column, *rotate* the prongs of the vibrating fork slowly until the sound ceases. Then slip a cylinder of paper over one prong. Explain.

c. Periodical changes in the loudness of a sound are called *beats.* Beats can be heard only when the component sounds differ very little in pitch, — that is, in vibration rates. It has been found that the number of beats per second is equal to the difference in the vibration rates of the two beating sounds. But the ear cannot distinctly separate more than about ten low sounds per second. Hence, beats more rapid than ten per second coalesce into a rough unpleasant sound or discord (§ 130, *a*, *c*). But, as the pitch rises the ear can detect the separate sounds in a more rapid succession, and hence the number of beats per second may increase without producing harshness. On this account intervals less than the minor third are less discordant in the higher parts of the scale (§ 130, *b*).

d. The resultant of two sounds may be silence. If the sound waves are *equal in length,* and *equal in amplitude,* and *interfere in opposite phases,* they will neutralize each other completely, because the algebraic sum of their amplitudes is zero (*b*, experiment).

IX. RADIANT ENERGY—HEAT AND LIGHT.

TRANSMISSION OF RADIANT ENERGY.

137. **The Ether.** — *a.* We have seen that physicists assume the existence of a medium called *ether*, in order to explain the transmission of energy when there is no solid or fluid matter to carry it (§ 20, *c*).

The ether must be a medium of extreme tenuity and perfect elasticity. It is supposed to fill the spaces between molecules, and to extend to the utmost bounds of space. In fact, molecules and masses of matter are supposed to be immersed in a boundless sea of ether, in which they move with perfect freedom, much as the fishes are immersed and move about in the water of the ocean.

b. The ether is supposed to transmit energy by waves. For example: Let a gas jet be lighted, and every eye in the room is affected instantly. In this case the vibrations of the intensely heated molecules of the gas create waves in the ether, and these ether waves convey their energy to the eye.

138. **Radiant Energy.** — *a.* The energy which resides in ether waves is called *radiant energy.* Radiant energy takes different names according to the kind of work which it does. Thus it is called *light* if it can affect the eye; *radiant heat* if it can raise the temperature of a body which receives it; *actinic energy* if it can produce chemical changes; and *electricity* if it can produce in matter certain conditions which are known as *electrification.*

b. The nature and laws of radiant energy are best illustrated

by the phenomena of light, and hence the following sections will be devoted chiefly to light.

139. **Radiant Energy is propagated in Straight Lines.** — *a*. Let *a* (Fig. 148) represent a red-hot bead. The ether waves go from it in all directions, and surround it like concentric shells. When the front of the wave has reached *b*, the energy in the wave at that point has gone in the straight line *ab*, and will go straight to *c*, and outward, as the wave rolls on. The path of a beam of light, in a partly darkened room, is often seen by the illuminated dust, and nothing could be straighter than it appears.

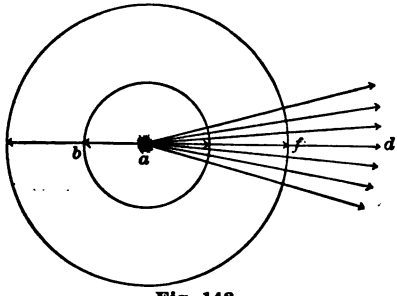


Fig. 148.

b. Straight lines which show the directions in which radiant energy is propagated are called *rays*. Thus, in Fig. 148, the lines radiating from *a* toward *d* are rays. *Diverging rays* are rays which separate more and more as they proceed. All rays given off from a common point, as *a*, Fig. 148, must be diverging. *Parallel rays* are rays which neither separate nor approach one another as they proceed (Fig. 149). Rays from a very

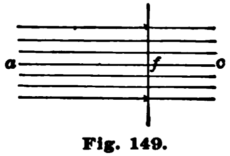


Fig. 149.

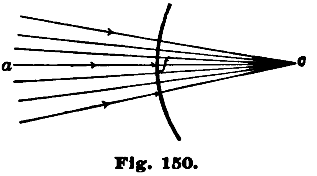


Fig. 150.

distant source — the sun, for example — are sensibly parallel; none can be absolutely parallel unless they proceed from different points in the body which sends them. *Converging rays* are rays which approach one another as they proceed (Fig. 150).

A bundle of parallel rays is called a *beam*. A number of rays proceeding from, or converging toward, a point, are called a *pencil*.

c. The wave front may be convex, as it must be if the rays are diverging; it may be plane, as it must be if the rays are parallel; or it may be concave, as it must be if the rays are converging. These three forms of wave front are represented at *f* in Figs. 148, 149, 150.

Any point from which rays diverge, as *a*, Fig. 148, or toward which they converge, as *c*, Fig. 150, is called a *focus*.

d. Light passes quite freely through water and glass, but not through iron. Any space or substance through which light can go is called a *medium;* and if it is exactly alike, in structure and properties, at all points, it is called a *homogeneous medium*.

e. Radiant energy starts from *every point* of a hot or luminous body to go in every possible direction. Thus heat and light radiate from every point in a candle flame, as shown for a few points by Fig. 151, and go in all directions from each, which cannot be shown without confusion of lines.

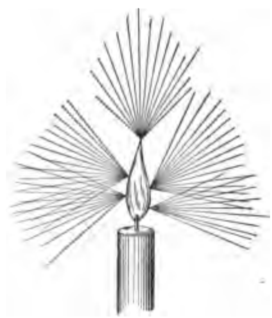


Fig. 151.

f. Media differ greatly in their power to transmit light. Some, like air and water, transmit it very freely, so that the forms of objects can be seen through them; such are said to be *transparent*. Others, like gold and wood, seem to forbid its passage, except in very thin plates; such are said to be *opaque*. Others, like ground glass, permit light to pass through but do not reveal the object from which it comes. These are said to be *translucent*. But no substance is perfectly transparent; even air and water arrest some portion of the light that enters them. On the other

hand, perhaps no substance is perfectly opaque; even through gold, if in thin sheets — gold leaf — some light passes.

Experiment 85. — *Object.* To study, by means of a "pin-hole camera," the straight-line propagation of light.

The pin-hole camera is a small, dark chamber or box. The front end is a sheet of cardboard with a large pin hole in its center. The other end is a sheet of ground glass or of oiled paper.

Place a candle flame some distance in front of the pin hole, and look for an image of the flame, tip down, on the glass or paper back. Do not expect it to be very sharply defined, but seek for the sharpest definition by changing the distance of the candle.

g. To explain the production of an image by means of a pin hole, draw the diagram (Fig. 152). Let *ab* represent the flame, *ff* the front of the camera, and *ss* the screen at the

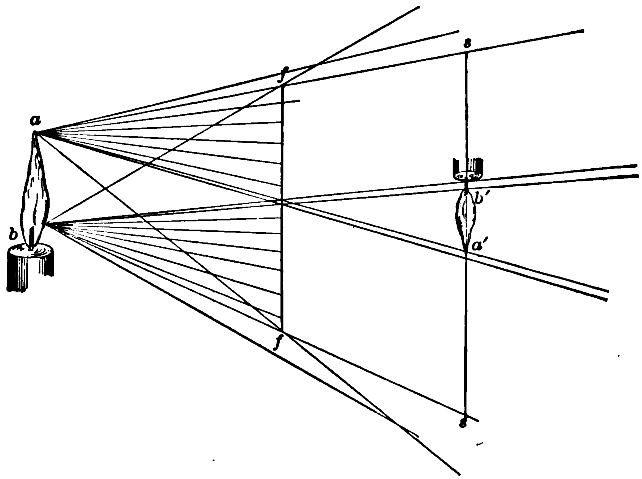


Fig. 152.

back. From the tip of the flame, *a*, a pencil of light goes out in all directions. The pin hole permits a few of these rays to reach *ss* at *a'*, while the opaque front *ff* shuts out all others. A pencil, likewise, goes in all directions from the base of the flame, *b*. A few of its rays enter the hole and reach *ss* at *b'*.

From every point of the flame, between *a* and *b*, a pencil proceeds, but only a few rays can pass the hole; these reach the screen *ss* at corresponding points between *a'* and *b'*. All these points of light on *ss* are arranged in the inverted order of those of the flame, because the rays from the upper and lower points, *by going in straight lines*, must cross each other in passing through the hole.

140. **Shadows.** — A *shadow* is space from which light is shut out by an opaque body. The existence of shadows is due to the fact that light is propagated in straight lines.

Thus let *a* (Fig. 153) represent a very small source of light, and *b* an opaque ball. Those rays which fall upon the surface of *b* are stopped, while those which graze its edge, and all

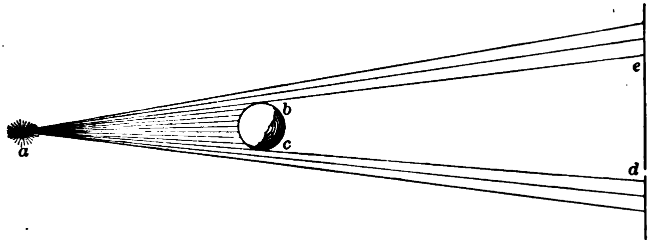


Fig. 153.

beyond those, go straight forward. So the space *bcde* receives no light, and that space is the *shadow* of the body. The shaded portions of the surfaces of walls and other bodies, which are usually called shadows, are only the cross sections of the real shadows, while the shadows themselves are geometrical solids.

Experiment 86. — *Object.* To study the distribution of light and shade in a shadow.

Apparatus. A cardboard screen to receive the shadow. The cardboard, about 20 cm. square, may be held upright by tacking it to one end of a square block. A slender rod to "cast the shadow." It should be about .5 cm. in diameter, and may be set into a block to hold it upright. A kerosene lamp with a broad wick, and two candles.

Operations. Place the lamp flame with its broad side toward the screen, say 60 to 80 cm. away, and the rod between the two, say, 10 cm. from the screen. Look for a shadow with a dark center, called the *umbra*, and lighter sides, called the *penumbra*. Move the rod until these two parts are most distinct. Try other objects, such as a ball or a disk, and detect the umbra and penumbra in each shadow.

Search for the cause of the unequal distribution of light and shade as follows: Place two candles side by side, facing the screen, say 60 cm. away. Put the rod, say, 10 cm. from the screen. Two shadows should be distinctly seen. Move the rod toward the screen until the shadows lie edge to edge, and then a little further. Look for a *single shadow made by the overlapping of the two*. You see why this shadow has an umbra and a penumbra. Explain.

In like manner the shadow made by the broad lamp flame *consists of overlapping shadows*. Remember that light *goes from every point of the flame* in straight lines to the screen. Only a point source of light could yield a shadow without a penumbra. Compare the shadows cast by the electric arc lamp with those of the same objects cast by the sun.

141. **The Optical Bench.** — An optical bench consists of a graduated bar upon which screens, and other pieces of the apparatus required in experiments with light, may be mounted

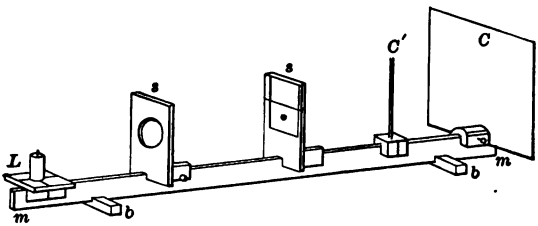


Fig. 154.

and moved into their proper places with precision. Much can be done without this instrument, as in the last experiment, but where measurements are to be made, some form of optical bench is very desirable. The following form (Fig. 154) has been found to be simple, cheap, and satisfactory.

mm is a meter bar, with sides vertical, supported by grooved blocks, *bb*. *s, s* are sliding supports for various articles needed in experiments. They consist of grooved blocks to slide along

the edge of the bar, carrying uprights which are *perpendicular to the bar in both directions*, vertical and horizontal. These uprights are made of thin wood, and are fastened upon the *ends* of the grooved blocks, so that the scale reading to be taken may be marked by the face of the upright. For screens, *C*, pieces of stiff white cardboard are tacked to the ends of the sliders. Wooden uprights *s*, *s*, with holes, are useful for many purposes. A slider with a platform, *L*, will support a candle or small lamp.

142. **The Intensity of Light.** — *a.* The intensity of light is the quantity of light which falls on a unit surface of an object. Thus the page of a book is more strongly illuminated by a good lamp than by a candle, even when it is the same distance away; that is, every square centimeter of it receives more light. In other words, the intensity of the light is greater.

The intensity of light depends on the light-giving power of the source. It also depends on the distance away from the source. We must first see how it depends on distance.

b. The further we take our book from the lamp, the less light does the page receive. Doubling the distance reduces the intensity to one fourth, and if the distance is made three times as great, the intensity of light is reduced to one ninth. In general: *The intensity of light varies inversely as the square of the distance from its source.* This is the *law of inverse squares* for light.

Experiment 87. — *Object.* To verify the law of inverse squares for light.

The apparatus consists of an optical bench, with three screens and a kerosene lamp or candle (Fig. 155). The light, *L*, is placed near the end of the bar. The first screen, *S*, consists of a card pierced with a hole .3 cm. in diameter, bound by a rubber band over the large hole in one of the wooden uprights. The faces of screens *C* and *C'* are covered with cross-section paper. This paper is accurately ruled in small, equal squares. Cut out of *C* a centimeter or a half-inch square, by carefully following the lines with a sharp knife. The brightest part of the flame, the hole

in S, and the middle of the window in C, must be at equal heights. The object of the hole in S is to make the edges of the patch of light on C' as sharp as possible; put it very near the flame. Now *the same quantity of light that, starting from L, goes through S, fills the window, w, and is diffused over the larger surface, p.* Its intensity must be less as the surface which it covers is larger. Thus if p is 4 times w, then the intensity of the light at p is $\frac{1}{4}$ the intensity at w.

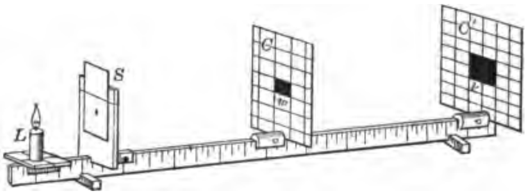


Fig. 155.

Place C at 15 cm. from L, and C' at twice that distance. Count the number of half-inch squares in the patch of light on C'. Repeat, with C' at 3 and 4 times the distance of C from L, and also with C at other distances. Record the distances and the areas in a table. If you find that when C' is 2, 3, 4 times the distance of C from L, the areas of p are 4, 9, 16 times the area of w, then the intensities of light would be $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{16}$, and the law is verified.

143. **Photometry.** — *a.* A good lamp yields more light than a candle, so that bodies *at equal distances* from them will be illuminated more intensely by the lamp. Perhaps it would take 16 candles to make the light on a screen as intense as the lamp does. If so, then the *light-giving power* of the lamp is 16 times that of the candle. Wax, oil, gas, and electric lamps differ greatly in their light-giving, or illuminating, power. *Photometry* is any process for comparing the light-giving power of different sources of light. The instrument employed is called a *photometer*.

b. The unit usually employed to measure the light-giving power of different sources of light is the light-giving power of a sperm candle which burns at the rate of 120 grams per hour. This unit is called a *candle-power*.

c. Photometry is based on the law of inverse squares. If

at twice the distance from a light the intensity must be $\frac{1}{4}$ as great, then a source that would emit 4 times as much light would make it equally great. The same reasoning is good for all such cases. In general: *The light-giving power of two sources of light must be to each other as the squares of their distances from a screen on which they give equal intensities.*

d. In the *Rumford photometer*, a small rod is placed near a screen, and the two lights are placed at such distances that the two shadows are equally dark, which shows that the screen is lighted with equal intensities. The distances from the screen are measured and their squares compared.

Experiment 88. — *Object.* To compare the light-giving power of a kerosene lamp with that of a candle by means of a Rumford photometer.

The photometer. — A cardboard screen, C', is nailed to the face of a wooden block, s, in which a wooden rod is set upright, about 4 cm. from C' (Fig. 156). The zero ends of two meter bars are placed on the block, both touching the rod, while the other ends are supported by grooved blocks. The rod is not tightly held in the hole.

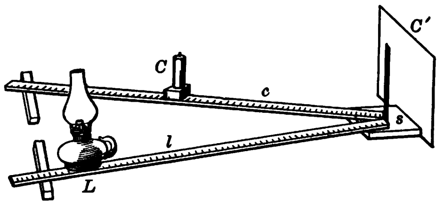


Fig. 156.

Operations. — Place the candle on one bar, and a lamp on the other. Adjust the flames to about equal heights. Adjust the angle between the bars so that the two shadows of the rod shall lie edge to edge without overlapping. See that the bars are equally inclined to the screen. Place the candle at a convenient distance — say 30 cm. — from the screen. Place the lamp flame almost edgewise toward the screen, and move it back and forth until the shadows are equally dark. Note the distances, c and l, of the candle and the lamp from the screen; they are the scale readings at the centers of the flames, with the distances of the zero points from the screen added. To get these distances, remove the rod and measure the prolongation of the inner edge of each bar of the screen. Repeat with the candle at different distances, tabulating the results:

TRIAL.	c	l	c^2	l^2
1				
2				
3				

The light-giving power of the lamp is $\frac{l^2}{c^2}$ times that of the candle. If a standard candle (b) is used, then $\frac{l^2}{c^2}$ is the candle-power of the lamp.

e. If a spot on a sheet of paper is saturated with paraffin or oil, it will transmit light quite freely. If the sheet is more strongly lighted on one side than the other, the spot will appear darker than the paper on that side, but lighter than the paper if viewed from the other side. Try it. If both sides are equally lighted, the spot becomes quite, or nearly, invisible.

f. In the *Bunsen photometer* a paper screen, with a translucent spot, is placed between the two sources of light, and their distances adjusted until the spot is equally invisible when viewed from opposite sides. The distances of the sources of light from the screen are then measured.

Experiment 89. — *Object.* To compare the light-giving power of a lamp with that of a candle, by means of a Bunsen photometer.

Put two optical benches in a straight line, with their zero ends together. Mount the screen with its translucent spot directly over the zeros. Mount the lamp on a platform slider near the distant end of one bench, and a candle on the other bench. By trial find a place for the candle such that the spot is equally indistinct when viewed from opposite sides. Note the distance, l, of the lamp, and c, of the candle, from the screen. Repeat, choosing a different distance for the lamp. Tabulate observations and results as in the preceding experiment. $\frac{l^2}{c^2}$ is the light-giving power of the lamp in terms of the candle.

The photometer screen should receive no light from any source but the lamp and candle. Hence darken the room, or set up other screens to shield the photometer screen.

144. The Speed of Light. — *a.* The passage of light from place to place seems to be instantaneous. It was supposed to be so until 1675 when Roemer, a Danish astronomer, discovered that light from one of the moons of Jupiter requires about 16 minutes and 36 seconds to traverse the diameter of the earth's orbit — a distance of about 185,000,000 miles. This would give the speed of light nearly 186,000 miles per second.

b. Roemer's observations may be understood by means of the diagram (Fig. 157). Let *ee'* represent the earth in its orbit around the sun at an interval of a half year between the two positions; *J*, Jupiter in the sunlight with its shadow, and *m*,

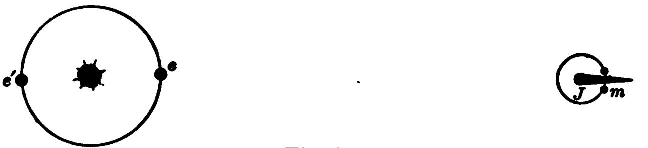


Fig. 157.

the nearest of his four moons. This moon passes through the shadow, and is eclipsed every two days. The exact time when each eclipse actually begins is computed by astronomers, but Roemer observed that an eclipse always appears to begin a little later, when the earth is receding from Jupiter, and put the difference in time at 22 minutes for the two positions *e* and *e'*. From this fact he inferred that light requires that length of time to cross the earth's orbit from *e* to *e'*.

Roemer's inference was right, but his measurement of time was wrong. Delambre afterward found it to be 16 minutes and 36 seconds.

c. The speed of light has been found by more reliable methods since the time of Roemer (Barker's Physics). According to Newcomb the speed of light, in space, is 186,328 miles, or 299,860 kilometers, per second. It is a little less in air, and still less in transparent liquids and solids.

REFLECTION OF RADIANT ENERGY.

145. **A Division of the Beam.** — *a.* Whenever radiant heat or light falls upon the surface of a body in its pathway, it is divided into two parts: one part enters the body, and another part is thrown back into the medium through which it came.

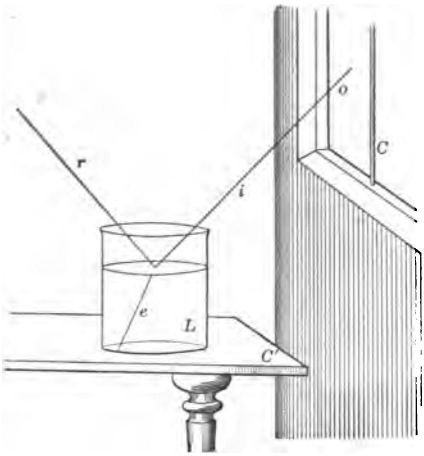


Fig. 158.

Experiment 90. — *Object.* To witness the division of a beam of light at the surface of water.

Let a beam of sunlight enter a partly darkened room through an opening in a window shutter. Place a jar of water on a table to receive the beam (*i*, Fig. 158). Look for its two parts, — *e*, which enters and traverses the water, and *r*, which is thrown off into the air. A drop or two of milk, or a very little soap solution, added to the water will make the pathway of *e* distinctly visible, and a little dust sprinkled in the air by striking two blackboard brushes together will reveal the path of *r*.

b. That part of the incident beam which is turned back into the medium from whence it came, is said to be *reflected;* and the action by which it is thrown back from the surface is called *reflection.* For the present we will attend to this reflected portion only, and leave that which enters the second medium for future study.

146. **Reflection of Heat and Light.** — The reflection of radiant heat and light is the reflection of ether waves, and the reflection of ether waves is analogous to that of water waves and sound waves (§ 113). It obeys the same law (§ 120, *c*), and

the same terms (§ 120, *b*) are used to describe it. The student should therefore carefully review these subjects.

Experiment 91.—*Object.* To verify the law of reflection as applied to light.

The *apparatus* consists of a candle to give the light; a small mirror to reflect it; a graduated circle with which to measure angles; and a small screen with a hole, through which to receive the reflected light into the eye. These are set up as shown in Fig. 159. The mirror, *m*, carries a narrow strip of paper, *p*, fixed upon its face with gum, or a narrow line scratched through the silvering on the back. It is held vertically by a bar, *b*, the wood being cut away so that the face of the glass is flush with its surface. The graduated circle *C′* is tacked upon a smooth block. The bar is laid upon it with its edge exactly coinciding with divisions 90° from the zero, and the foot of *p* exactly at the center. Two threads are fastened to the bar at the foot of *p* exactly over the center of the circle. The other end of one is loosely looped over the candle; that of the other is fixed to the screen *C*, at the foot of a vertical line drawn through the center of the hole.

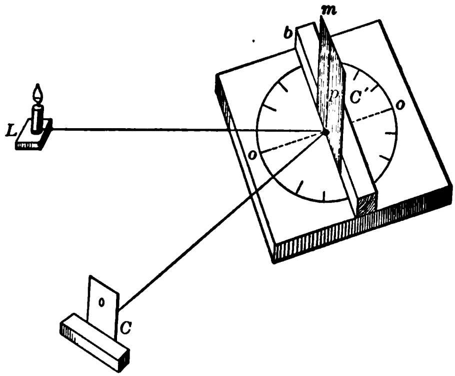


Fig. 159.

Operations. Draw the candle until its thread is straight, and makes any convenient angle with *oo*. See that the loop slides around the candle instead of bending the thread at its surface. Draw *C* away until its thread is tense, and move it until by looking through the hole you see the image of the flame centered exactly on *p*. Then read the angles of incidence and reflection. Move the candle and repeat the observations several times. Tabulate the results, draw your conclusion, and compare it with the law (§ 120, *c*).

Number of Trials.	Angle of Incidence.	Angle of Reflection.
1	....	....
2	....	....
3	....	....

147. **Smooth and Rough Surfaces.** — *a.* If the reflecting surface is smooth, a large part of the light received upon it is "regularly reflected;" but if it is rough, the light is "diffused." The difference in the two cases is shown by Fig. 160, in which

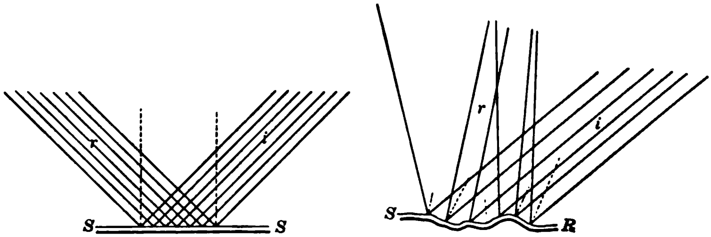


Fig. 160.

SS represents a perfectly smooth plane surface, and *SR* a surface like that of most bodies as they actually are — more or less rough. The angles of incidence and reflection must be equal *at every point of the reflecting surface.* If the points are not regularly arranged, the reflected rays must be scattered.

b. Light, entering the eye, produces vision. But it is not the light which we see, for light itself is absolutely invisible. We see *objects* by means of light which they send to the eye. Luminous bodies, such as a candle flame or red-hot iron, originate the light which they send to the eye, but other bodies are seen by light which they reflect. Moreover, the light which renders an object visible is the light which it *scatters* by reflection.

c. A perfectly smooth body would be invisible, because regularly reflected light affects the eye as if it came directly from its source instead of from the object which reflects it; it produces an image of the object which sends it to the reflector. Thus when a person sees his own image in a looking-glass, the rays which go from the person to the glass are regularly reflected back to his eyes; he scarcely sees the glass itself. But the light which is diffused by a body on account of any

roughness of its surface, enables us to see the body which reflects it.

d. A surface so smooth and opaque that a large part of the light it receives is regularly reflected is called a *mirror*. A *plane mirror* is one whose reflecting surface is plane. A *spherical mirror* is one whose reflecting surface is a portion of the surface of a sphere. It may be convex or concave.

148. **Plane Mirrors.** — *a.* The common looking-glass is a plane mirror. The glass itself is not opaque, and comparatively little light is reflected from its front surface; but the mercury film upon its back is both smooth and opaque, and reflects nearly all the light that reaches it. This mercury surface is the real mirror. The most perfect mirrors are metal plates with highly polished surfaces, or glass plates coated *in front* with a thin layer of highly polished silver.

b. The image of a point is another point from which the light of the first comes, or appears to come, after reflection.

Thus, in Fig. 161, *MM* represents a section of a plane mirror, and *p* the tip of a candle flame. Light from the point *p* goes out in all directions (§ 139, *e*). A portion covers the surface of *M* and is reflected by it. The rays reflected from *ab*, which is so small a part of the surface that the diverging rays reflected from it will not separate too far to enter the small pupil of an eye, enter the eye, *E*, as if they came from the point *p′* instead of *p*. The tip of the flame appears to be at *p′*; so *p′* is the image of *p*.

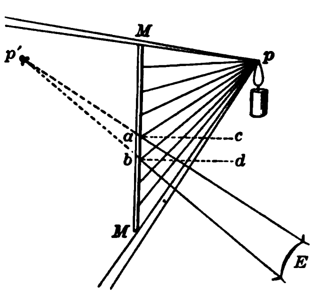


Fig. 161.

c. The direction of the rays reflected at *ab* may be traced as follows: Erect perpendiculars *ac* and *bd* at the points of incidence; the angles *pac* and *pbd* are the angles of incidence.

According to the law (§ 146) there must be angles of reflection equal to these. Hence draw the lines *aE* and *bE* so that *caE* equals *pac*, and *dbE* equals *pbd*.

No light actually comes from *p'*; the rays *aE* and *bE* only appear to. Hence the image is called a *virtual image*.

d. The image of an object consists of the images of all its points.

Thus, in Fig. 162, let *MM* represent a section of a plane mirror, and *Pb* a candle in front of it. Draw two rays from *P* to the mirror, and erect perpendiculars, *c* and *d*, at the points of incidence. You thus find the angles of incidence. Then draw two rays to make equal angles on the other side of *c* and *d*. Prolong these rays backward to find the image, *P'*, of the tip. Next trace two rays from a point, *b*, on the base of the candle in the same way, and prolong them backward to find the image of *b* at *b'*. Now the images of all points of the candle between the extreme points *P* and *b* would lie between *P'* and *b'*. In fact, there is an image of every point of the candle, and these images are arranged in the same order as the points themselves, and constitute the image of the candle.

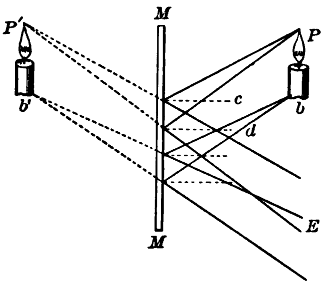


Fig. 162.

Experiment 92. — *Object.* To compare an object with its image in a plane mirror.

1. As to size . . . . by measurements.
2. As to distance from the reflecting surface by measurements.
3. As to lateral inversion . . . . by inspection.

Apparatus. The mirror (Fig. 163) consists of a sheet of *plate glass* (window glass is often warped so that its surface is not a plane mirror). One end rests in a saw-cut in a block of wood, and care should be taken to make the glass vertical. A meter bar, *m*, a candle, a screen, *C'*, and a bottle filled with water, are required. The room need not be darkened.

Operations. Put the meter bar under the glass *C*, as shown. Stand the lighted candle on the bar in front. Looking through *C* from the candle side, you should see the image of the candle.

Put the bottle of water on the bar behind *C*; move the candle along the bar, and swing the bar sidewise, if necessary, until the image appears to be inside the bottle of water. Now compare the image with the flame, — as to size, and distance from the mirror.

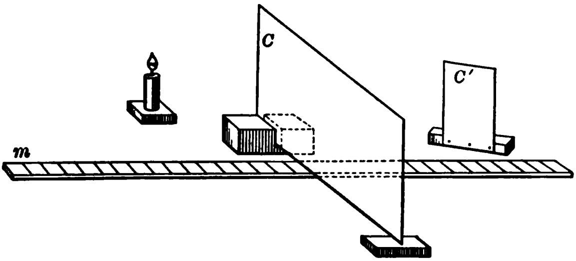


Fig. 163.

But to be more exact: Substitute the screen *C'* for the bottle; place it and the flame with their centers over the middle line of the bar, and make the bar perpendicular to the mirror. Move the candle until its image seems to be accurately fixed on *C'*. Note the distances from the *front surface* of the glass to the center of the flame and to the brighter of the two images. Repeat with different distances. One can use an unlighted candle, of the same height as the other, in place of *C'*. Move the flame until its image is on the wick of the unlighted candle.

Number of Trials.	Distance of Flame.	Distance of Image.	Relative Sizes.
1			
2			
3			

Look toward the candle from the mirror; mark its right-hand side; see whether the mark appears on the right-hand side of the image. Remember, if you can, whether your image in a mirror is likewise reversed.

e. An image formed by a plane mirror is virtual. It is of the same size as the object, just as far behind the mirror as the object is in front, with every point exactly opposite the corresponding point of the object.

f. Multiple images,—more than one image of one object at the same time,—may be obtained by plane mirrors. Two, and often more, are sometimes seen in a single mirror. The *front surface* of the glass reflects light enough to produce one image, and the larger part of the light, which goes through the glass, is reflected from the mercury surface behind, and yields a brighter image. When the glass is thick, the two may be quite separate. Try a hand glass with a candle flame, or, better, a bright star. Even unsilvered window glass gives the double image by reflection from both surfaces (Experiment 92).

g. But multiple images are produced to the best advantage by the use of two or more mirrors, as may be found by the following experiment:

Experiment 93.—Place two looking-glasses on the table, inclined to each other at, say, 60°, and stand a lighted candle between them. A circle of images may be seen in the mirrors (Fig. 164), and the number will increase or diminish as the angle is made smaller or larger. One's own face may be the object, and the curious relation of the images in pairs will be more marked.

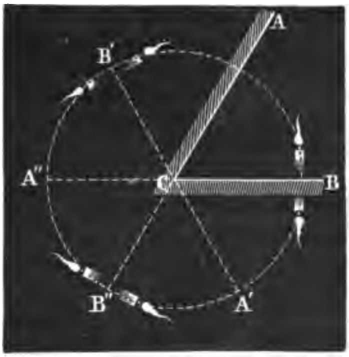


Fig. 164.

h. Multiple images are produced by repeated reflections. Thus the light of the candle covers both mirrors. Some of the rays being reflected from each mirror enter the eye, and produce the first two images in the circle. Other rays are reflected from one mirror against the other, which then reflects them to the eye; by this double reflection the second two images in the circle are produced, and by a threefold reflection, the eye sees the third pair.

i. The *kaleidoscope* produces beautiful color effects by multiple reflection. It consists of three strips of looking-glass,

encased in a tube, with their edges together at an angle of 60°. Bits of colored glass are placed loosely between two disks, — one of them of ground glass, the other clear, — which close one end, while a cap with a small hole closes the other. Looking through the small hole toward a source of light, one sees the numerous images of the bits of glass arranged in symmetrical patterns of great beauty, changing marvelously with movements of the instrument.

149. **Concave Spherical Mirrors.** — *a.* The inside of a bright silver spoon is concave, and curious images may be discovered therein: It is a concave mirror (§ 147, *d*). A polished concave surface of any form is a *concave mirror*, but the most common and useful are spherical. A *spherical concave mirror* is a polished portion of the inside surface of a hollow sphere.

The reflection of a beam of light by a spherical concave mirror may be studied as follows:

Experiment 94. — Hold a concave mirror across a beam of sunlight in a darkened room, so that the central ray is perpendicular to the mirror at its middle point (Fig. 166). Look for a luminous point, on the central ray, into which the reflected rays are gathered, and from which they again diverge. Turn the mirror a little out of the perpendicular; look to see this focus (§ 139, *c*) move out of the incident beam. The slightest inclination carries the focus away from the central ray.

b. Fig. 165 represents a section of a concave mirror as a portion of the inner surface of a hollow sphere whose center is *C*. Fig. 166 represents in section the reflection of sunlight when a concave mirror is perpendicular across the beam. Fig. 167 represents the reflection of sunlight when a concave mirror is held obliquely across the beam. These three figures are intended to illustrate the form and action of concave mirrors, and to show the meaning of the following terms:

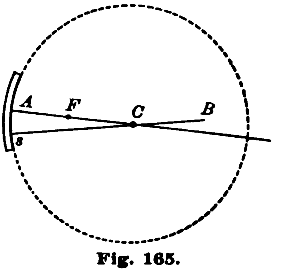


Fig. 165.

The *center of curvature* (*C*) is the center of the sphere of whose surface that of the mirror is a part. The *vertex* (*A*) is the middle point of the reflecting surface. The *principal axis*

Fig. 166.

(*CA*) is a line drawn through the center of curvature and the vertex. Any other line (*Bs*, Fig. 165) drawn through the center of curvature to the mirror is called a *secondary axis.* The *principal focus* (*F*) is a point on the principal axis almost half way between the vertex and the center of curvature. At

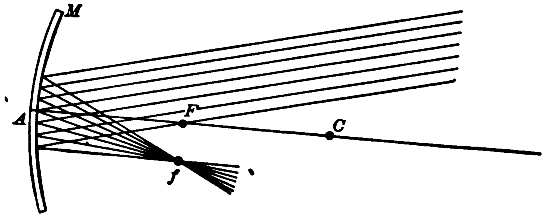


Fig. 167.

this point all rays parallel to the principal axis, and not far away from it, cross after reflection.

c. The student should be able to represent the reflection by a diagram. To do this he must apply the law of reflection, *i.e.*, he must construct angles of reflection equal to angles of incidence. Thus take one ray from the tip of a candle flame. Draw a line *pb* (Fig. 168) to represent the ray which reaches a mirror, *M*, at *b*, and find the direction in which it is reflected.

To find the angle of incidence, erect a perpendicular to the mirror at *b*. Now, *a line from any point of a spherical surface to the center of curvature is perpendicular to the surface at that point.* Hence draw the dotted line *bc*. Then *pbc* is the angle of incidence. Draw *bp′*, making an equal angle on the other side of *bc*, and *bp′* is the direction of the reflected ray. In this way one can trace the reflection of any ray or any number of rays.

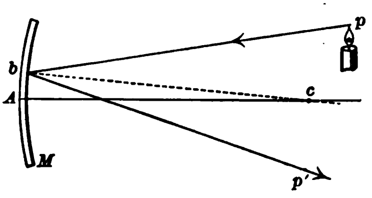


Fig. 168.

d. Every ray that passes through the center of curvature to the mirror must pass back through the center of curvature after reflection, because the angle of incidence is zero.

Every ray that goes parallel to the principal axis on its way to the mirror, if it is not too far away from the axis, must go through the principal focus after reflection (§ 149, *b*).

These two facts will enable us very often to simplify our diagrams by omitting the perpendiculars. We may, for example, trace the reflection of a pencil of light from the tip of a candle flame as follows:

Choose a center, *C* (Fig. 169); draw an arc, *MM*, to represent the mirror; draw the principal axis, *AC*, and mark the principal

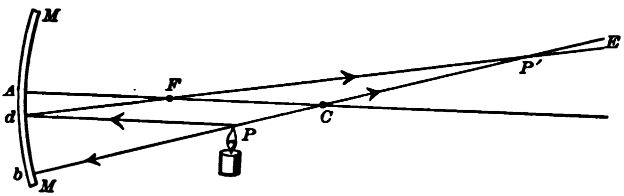


Fig. 169.

focus, *F*, half way from *A* to *C*. Let *P* represent the tip of the flame. Take two rays to represent the pencil that covers the mirror, — one, *Pb*, as if it had come through *C*, the other, *Pd*,

parallel to the principal axis, *CA*. The former, *Pb*, will be turned back upon itself, and go on through *C* toward *E* after reflection. The latter, *Pd*, will be reflected through *F* and on toward *E*. The two reflected rays cross each other at *P'*.

150. **Images by Concave Mirrors.** — *a.* Concave mirrors produce real images. Thus if the eye is placed at *E* (Fig. 169), the light from the tip of the flame, after being reflected by *M*, would appear to have come from *P'*; hence *P'* is the image of *P*. It is a *real* image, for the light actually does go from it to the eye after reflection (compare § 148, *c*). If a sheet of white paper is placed at *P'*, the image of the flame will be seen lying upon it.

Experiment 95. — *Object.* To obtain the real image of a candle flame by a concave mirror.

Place the mirror, *M* (Fig. 170), facing the screen, *L*, at a distance of about 1 m., and a lighted candle, *C*, near by. The candle and the screen

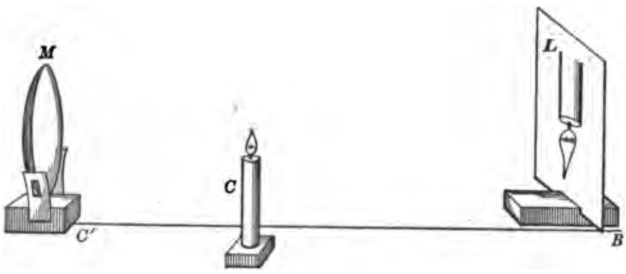


Fig. 170.

should be on opposite sides of a line *BC'*, perpendicular to the plane of the mirror. The room should be partially darkened. Then move *C* slowly away from *M*. When the proper distance is reached, the real image of the candle flame will be clearly defined on *L*.

Experiment 96. — *Object.* To find the focal length of a concave mirror.

Place the mirror across a beam of direct sunlight in a room partially darkened, as shown in Fig. 167, except that its inclination to the beam is *much less* than represented. Move a cardboard screen back and forth in the reflected pencil until the spot of light *f* — the image of the sun — is as small as it can be made, and then measure its distance from the vertex, *A*, of the mirror. Rays of light from an object so distant as the sun are

nearly parallel, and the spot f, on the screen, is *nearly* in the principal axis of the mirror. Hence its distance from the vertex is *nearly* the focal length of the mirror.

The optical bench may be used with advantage in making this experiment. The bench may be inclined so as to make the mirror face the sunbeam.

Experiment 97. — *Object.* To find what changes in the image are produced by changing the distance of the object from the mirror.

Mount a small concave mirror on one end of an optical bench; it may be bound by rubber bands to one of the supports. Place a screen on the table at one side of the other end of the bar. Stand the candle on the other side of the bar and near the mirror. The room should be partially darkened.

1. Move the candle toward the screen until its image is sharply defined. The image will be brighter if it is shielded from the direct light of the candle. Observe whether the distance of the candle from the mirror is greater or less than the focal length of the mirror found by Experiment 96. Note the fact, and also note whether the image is larger or smaller than the object. Move the candle outward a little further, and observe that the image is blurred. Then move the screen toward the mirror until the image is sharply defined on the screen again, and note the change in the image due to the change in the position of the candle.

2. Find a place for the candle, c, which requires the screen to be at an equal distance from the mirror, and where the image, i, is of the same size as the candle itself. The distance from the vertex of the mirror to the midway point on the bar, between the candle and its image, is twice the focal length, AF, of the mirror. Record the facts in a table, thus:

Distance of c from M.	Distance of i from M.	Size of i.	Erect or Inverted.
$2 \times AF$	$2 \times AF$	Equal to c	Inverted

Make the distance of the candle more than $2 \times AF$. Note in the same table the distance of the image as more or less than $2 \times AF$, and also the other two facts in their proper columns.

Make the distance of the candle less than $2 \times AF$, and note all the facts. Finally place the candle at a little less than the focal length, AF, from the mirror, and try to find a place for the screen where the image will be as sharply defined as before. If you are unable to find such a place, it will show that, in this case, no *real* image is formed within

reach. But look into the mirror and observe a well-defined *erect* image larger than *c* and behind the mirror. Of course this image is *virtual*. Note the facts in the table.

b. The *real* images are explained by diagram (Fig. 171). *M* represents the mirror, *C* its center of curvature, *F* its principal focus, and *AF* its focal length. *Lt* is the candle. Two

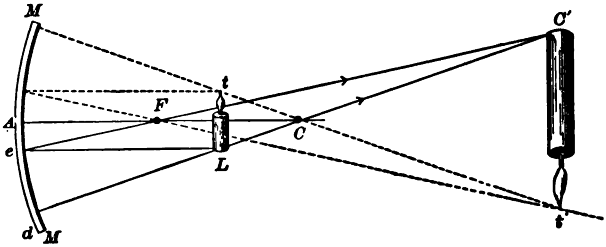


Fig. 171.

rays from *L*, — one, *Ld*, in line with the radius of the mirror, the other, *Le*, parallel to the principal axis, — are reflected, *Ld* back through *C*, and *Le* through *F*; they cross each other at *C''*, which is the image of *L* (*a*). Likewise two rays from *t*, shown by dotted lines, after reflection cross each other at *t'*, which is the image of *t*. The images of points between *L* and *t* would lie between *C''* and *t'*. Hence *C''t'* is the image of the candle.

c. The *virtual* images are explained by diagram (Fig. 172).

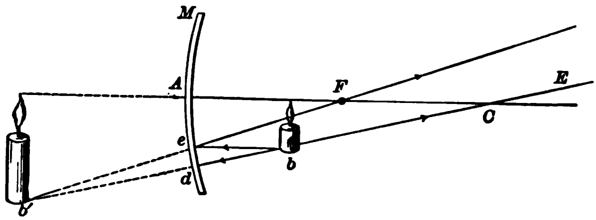


Fig. 172.

Two rays, *bd* and *be* (§ 149, *d*), from the base of the candle, after reflection pass one through *C* and the other through *F*. These

reflected rays diverge; they would never cross each other, but if they enter an eye placed in the direction of *E*, they would appear to have come from *b′* behind the mirror. Likewise rays from the tip of the flame would diverge after reflection, and appear to have come from behind the mirror. Hence the image complete is behind the mirror.

d. The description of images formed by concave spherical mirrors may be summed up as follows:

Case I. When an object is placed at less than the focal length in front of a concave mirror, the image is virtual, erect, larger, and more distant than the object.

Case II. When an object is placed between the principal focus and the center of curvature of a concave spherical mirror, the image is real, inverted, larger, and more distant than the object.

Case III. When an object is beyond the center of curvature of a concave spherical mirror, the image is real, inverted, smaller, and less distant than the object.

151. **Images by Convex Mirrors.**—The image formed by a convex mirror is always virtual, erect, and smaller and less

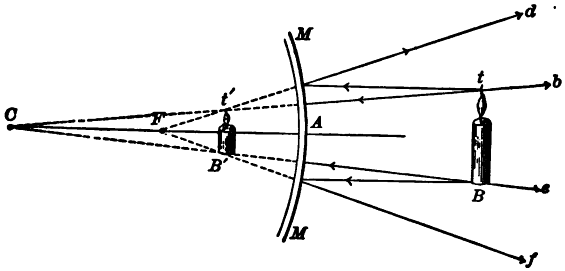


Fig. 173.

distant than the object. These facts should be studied with the mirror in hand, and then explained as follows:

In the diagram (Fig. 173) *M* represents a convex mirror whose center of curvature is *C*, principal axis *CA*, and principal

focus *F*. *Bt* represents the object, and *B't'* its image. By tracing two rays from each extreme point of the object (§ 149, *d*), they are found to diverge after reflection. To an eye which receives them, they would appear to have come from *B'* and *t'*.

REFRACTION OF RADIANT ENERGY.

152. **Division of the Beam.** — *a.* We have seen that when a pencil of radiant light or heat reaches the surface of a body, it is divided into two parts (§ 145, *a*). In this section we neglect the reflected part, already considered, and study the part which enters.

b. The radiant energy which enters a transparent body is divided into two portions. One part goes through and emerges as radiant energy; the other part is arrested by the molecules, and remains in the body as molecular energy (§ 90, *e*). For example: A lamp chimney transmits light, and is at the same time heated by energy from the flame within. The heat is the energy that is arrested by the molecules of the glass.

For the present we neglect the part which is arrested, or absorbed, and attend to that which is transmitted.

153. **Refraction.** — *a.* Whenever light passes obliquely from one medium into another whose density is different, its direction is changed (Fig. 158). This change in direction is called *refraction.*

In Fig. 174, I., let *a* represent a ray in air which reaches the surface of water at *i*. It is bent, or refracted, at that point, and goes on through the water in a new direction, *ib*. The ray *ai* is the incident ray; *ib* is the refracted ray, and *i* is the point of incidence.

Let *nn'* be drawn perpendicular to the refracting surface at the point of incidence, *i*. Then *ain* is called the *angle of incidence,* and *bin'* is called the *angle of refraction.* The angle of refraction is always in the medium into which the energy goes.

The angle *bic* shows how much the direction of the ray is changed; it is therefore called the *angle of deviation*. Resort to the apparatus if you would more clearly perceive the meaning of these terms.

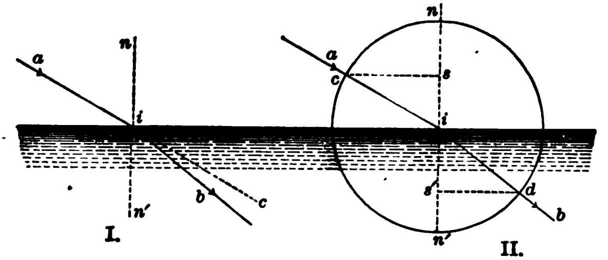


Fig. 174.

Proceed as directed in Experiment 90 (§ 145), and having thus obtained the incident and refracted beams *i* and *e*, hold a straight and slender wire vertically in the water at the place where the incident light strikes the surface, and ask yourself the following questions: What is the angle of incidence? What is the angle of refraction? Which is the larger, the angle in the rarer or that in the denser medium? Would this be true if the light were to strike the water more or less obliquely?

b. The angle in the denser medium is always the smaller angle of the two. Thus if light passes from air into water, the angle of refraction is less than the angle of incidence; but if light passes from water into air, — a ray *bi*, for example, — the angle of refraction is larger than the angle of incidence. Thus *ain* is larger than *bin'*. These facts enable us to see *which way* light is bent in passing from one medium into another, but they do not enable us to say *how much* bending occurs.

c. The exact relation of the angles is illustrated by Fig. 174, II. Take the point of incidence, *i*, as a center, and, with any radius, describe a circle. Draw the dotted perpendicular *nn'*, and from *c*, where *a* cuts the circumference, draw the line *cs* perpendicular to *nn'*. Also, from *d*, where *ib* cuts the circumference, draw *ds'* perpendicular to *nn'*. Now the length of *cs*

divided by the length of ds' will give the same quotient for all possible rays traversing these two substances.

d. Snell's law of refraction states the relation more precisely. Thus if the radius, *in*, is unity, then *cs* is called the *sine of the angle of incidence*, and ds' the *sine of the angle of refraction*, and Snell's law is stated as follows: *The quotient found by dividing the sine of the angle of incidence by that of the angle of refraction is a constant value so long as the two media are unchanged.* Written briefly the law stands:

$$\frac{\sin i}{\sin r} = n.$$

The constant quotient, n, is called the *index of refraction.* Any change in density of either medium fixes a new index of refraction.

A second part of the law of refraction states that *the incident and refracted rays are in the same plane as the perpendicular.*

e. Since the rays of light are bent in passing from one medium to another, it follows that what we see, when looking through transparent substances, are the *images* of objects beyond, and not the objects themselves. If a straight stick is partly immersed in still water, it will look bent at the surface of the water. Try this, with a lead pencil and beaker of water, and study the fact by means of a diagram (Fig. 175). The true place of the stick under water is shown by the dotted lines. The pencil of light which comes from the lower end is bent when it emerges from the water and proceeds to the eye, which traces it back as if it had not been bent, so that it appears to have come from a point

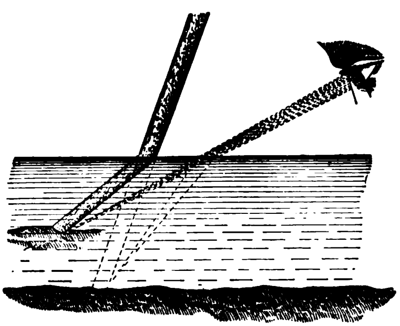


Fig. 175.

above that from which it started. Hence it is not the stick which is seen in the water, but its image. In looking through glass we see images instead of real objects.

Water does not appear to be as deep as it really is because the light which comes from the bottom is bent at the surface, and we see an elevated image of the bottom. Even when one looks *vertically* into the still, clear water of a lake it does not seem to be as deep as it really is, because all the rays in the pencil of light which comes from any point, *except the middle ones*, are bent at the surface. Thus the point *o*, at the bottom (Fig. 176), appears to be at some higher point, *o'*. The diagram exaggerates the effect.

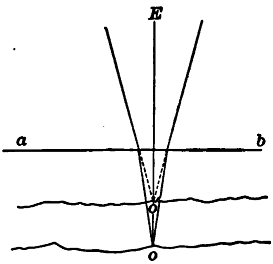


Fig. 176.

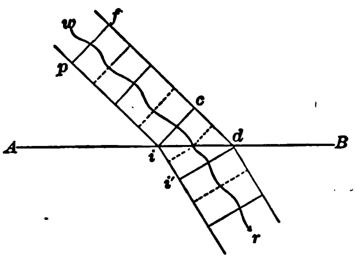


Fig. 177.

154. **Refraction explained.** — The refraction of radiant energy is due to the difference in speed with which it traverses the two substances. Michelson, by experiments made at Cleveland in 1883, proved that light goes 1.33 times faster in air than in water. And, in general, ether waves go more slowly in a denser medium.

A change in speed must cause a change in the direction of a wave. Thus let *AB* (Fig. 177) represent the surface of water, and *w* a wave with a plane front, *pf* (§ 139, *c*), passing toward it through air. The point *i* of this wave front must enter the water first, and will be traveling in water while *c* is traveling in air from *c* to *d*. But *c* goes 1.33, or $\frac{4}{3}$, times faster than *i*,

so that when c has reached d, i has gone only $\frac{3}{4}$ as far,—to i'. Hence $i'd$ becomes the wave front in the water. This new wave front faces toward r instead of in the direction in which the wave was going in the air. If the wave were going from water into air, it would be swung around the other way, because it would go $\frac{4}{3}$ as fast in air as in water.

155. **Direction of Transmitted Rays.**—*a.* The directions of rays after passing through a transparent body depend on the *shape of that body,* as well as on the index of refraction. Plates, prisms, and lenses are three typical forms.

A *plate* is a transparent body whose opposite sides are plane and parallel (Fig. 178). A *prism* is a transparent body whose opposite sides are plane but not parallel (Fig. 179). A *lens* is a transparent body of whose two opposite surfaces, at least one is curved (Fig. 180).

Experiment 98.—Use a rectangular paper weight as the *plate* to be used. Hold a lead pencil behind the paper weight, and look through the glass obliquely toward it. That part of the pencil which is behind the glass appears to be cut out and displaced (Fig. 178, I.).

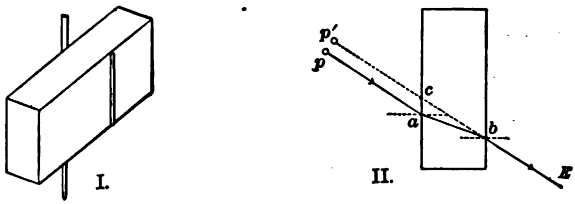


Fig. 178.

The fact is that the rays from each point of the pencil are bent when they enter the glass, and they are bent the other way just as much when they emerge. Hence *every emergent ray is parallel, but not coincident, with its incident ray.* Trace the course of a ray from one point for illustration. The ray pa (Fig. 178, II.), on entering the denser glass makes an angle of refraction less than the angle of incidence (§ 153, *b*), and then on emerging at b it makes an angle of refraction greater than its angle of incidence. The displacement of the rays which enter the eye, E, causes a virtual image of p in the direction Ep'. In the case of a thinner plate, like window glass, the displacement is proportionally less.

Experiment 99. — Use a glass triangular prism. The angle formed by the intersection of two plane surfaces of the prism is called the *refracting*

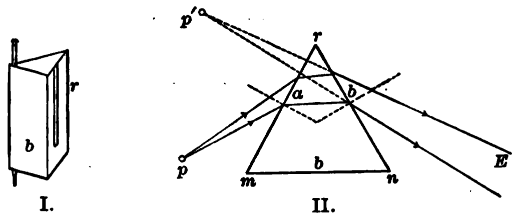


Fig. 179.

angle (see *r*, Fig. 179, I. and II.); and the surface, *b*, opposite *r*, is called the *back*.

Fix the prism upright, and look obliquely toward its refracting angle, while you hold a lead pencil on the other side near the back. That part of the pencil which is behind the prism appears to be cut out and displaced (I.). The fact is that the rays from each point of the pencil are bent toward the back, when they enter the prism, and they are again bent toward the back or in the same way, when they emerge. Hence the emerging rays are not parallel to the incident rays, and the displacement is greater than if the sides were parallel. In Fig. 179, II., *mnr* represents a section of a prism, and *p* a section of the lead pencil. The paths of two rays from *p* are shown. Trace them according to the law of refraction. They enter the eye at *E*, and appear to come from *p'*. Hence *p'* is the virtual image of *p*.

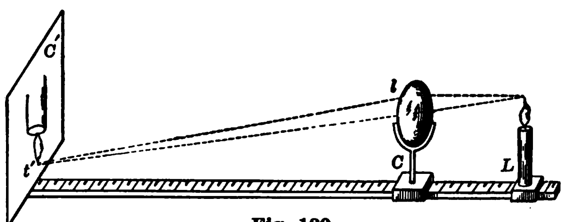


Fig. 180.

Experiment 100. — Use a convex lens. Place a lighted candle at one end of a meter bar (optical bench) and a white screen at the other. Then hold a convex lens, *l* (Fig. 180), between the two. Beginning near the candle move the lens toward the screen. A place may be found, in fact two places, where a well-defined inverted real image will be formed upon the screen. The fact is that the rays from each point of

the flame are bent toward the middle of a convex lens when they enter it, and again in the same direction when they emerge. After refraction the rays converge to a point on the screen, and the screen reflects them to the eye. Hence the image is seen on the screen.

b. Let *LL* (Fig. 181) represent a section of the convex lens, *c* the center of curvature of the right-hand surface, *c'* that of the left-hand surface, and *t* the tip of the flame. Carefully trace two rays from *t*. The dotted line from *c* is perpendicular to the surface at the point where one of them enters, and that from *c'* is perpendicular to the surface where it emerges. On entering the glass the angle of refraction must be less than

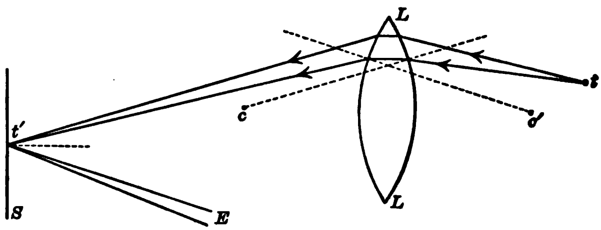
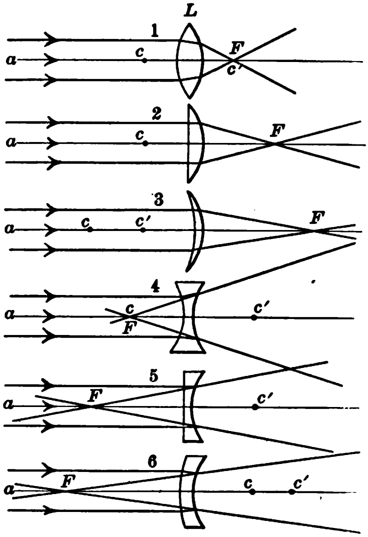


Fig. 181.

the angle of incidence (§ 153, *b*); on emerging, the angle of refraction must be greater than the angle of incidence. Hence the ray is bent toward the axis of the lens at both surfaces. So likewise is the other ray, as shown, and thus the two converge to the screen at *t'*. At *t'* they are reflected to the eye, which thus beholds the image on the screen. If *S* were a mirror, the eye would need to be placed at *E*, but being a rough surface it reflects the rays irregularly (§ 147, *a*), and the image is visible from all places in front.

156. **Lenses.** — *a.* There are six typical forms of lenses; they are represented in sections in Fig. 182. The centers of curvature of opposite faces are *c* and *c'*. A line, *acc'*, drawn through the centers of curvature, is called the *principal axis*, or often briefly, *the axis.* Fig. 182 shows not only the shape of

each variety of lens, but also its *name* and its *effect on parallel rays.* It will be seen that such rays are made converging by some and diverging by others. All the facts exhibited by this tabular view of the lenses should be carefully studied out.



Double Convex. — Parallel rays become converging by refraction.

Plano Convex. — Parallel rays become converging by refraction.

Concavo Convex. — Parallel rays become converging by refraction.

Double Concave. — Parallel rays become diverging by refraction.

Plano Concave. — Parallel rays become diverging by refraction.

Convexo Concave. — Parallel rays become diverging by refraction.

Fig. 182.

b. The six varieties of lens are included in *two classes:* There are the thin-edged, or converging, lenses, 1, 2, 3, and the thick-edged, or diverging, lenses, 4, 5, 6. Thin-edged lenses, in most cases, produce *real* foci (*F*). Thick-edged lenses, in all cases, produce *virtual* foci (*F*). These facts are shown in the cut.

c. The *optic center* of a lens is a point on the principal axis such that any ray passing through it is equally bent, and in opposite directions, at the two surfaces. For these rays the lens is equivalent to a plate (§ 155, *a*). Thus the ray *AB* (Fig. 183) is refracted at *a,* and then at *b,* and *bB* is parallel to *Aa.* Now the point *o* where this ray crosses the principal axis

is the optic center; but the displacement of a ray passing through the optic center of a thin lens is so slight that it may be neglected in the construction of diagrams. The curvature of most lenses is slight, much less than is represented in the diagrams. Any line passing through the optic center of a lens is called a *secondary axis.*[1]

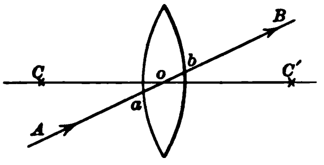


Fig. 183.

d. The *principal focus,* F, of a lens is the focus of rays which reach the lens parallel to and near the principal axis (Fig. 182). The *focal length* of a lens is the distance of its principal focus from the lens.

Conjugate foci are two points so related that light going from either one will be directed toward the other after refraction. In Figs. 180 and 181, t and t' are conjugate foci. So likewise are p and p' (Fig. 179). Thus *a point and its image are conjugate foci.*

Experiment 101. — *Object.* To find the focal length of a convex, or thin-edged, lens.

Mount the lens on an optical bench, and place it squarely across a sunbeam in a partially darkened room. Mount a screen behind the lens, and change the distance between them until the image of the sun is as small as it can be made. The distance between the image and the optic center of the lens is the focal length. If the lens is quite thin, the thickness of the glass may be neglected without sensible error. Try a plano-convex lens, first with its plane side, then with its convex side, toward the incident light. Note the difference.

In the absence of a sunbeam, direct the face of the lens toward a distant object, such as a tree or cloud, seen through a window, and receive its image on the screen. Make the image as sharp as possible. Its distance from the lens is *nearly* the focal length sought.

---

[1] If the lenses 1 and 4 (Fig. 182) have equal curvatures, their optic centers are midway between the surfaces. In lens 2 the optic center is on the convex surface. In lens 5 it is on the concave surface. In lenses 3 and 6 it is outside the surfaces.

Experiment 102. — *Object.* To ascertain what changes in an image are due to changes in the distance of the object from a convex lens.

I. Mount a lighted candle on one end of an optical bench. Mount the lens at a distance from the candle equal to twice the focal length (d) of the lens. Then find a place for the screen where the image is most sharply defined. Describe the image by stating four facts:

1. Whether it is real or virtual.
2. Whether it is erect or inverted.
3. Whether its distance from the lens is more or less than twice the focal length.
4. Whether it is larger or smaller than the object.

II. Place the lens at a distance from the candle a little greater than its focal length. Sharpen the image by moving the screen, and describe it as before. Move the lens gradually until it is again at twice its focal length from the candle, and describe the *changes* in the image.

III. Make the distance between the lens and candle a little greater than twice the focal length of the lens; sharpen the image and describe it in full. Move the lens gradually to greater distances, until the image when sharply defined is as small as it can be made, and describe the changes which it has undergone. Also note its distance from the lens, and compare it with the focal length of the lens.

IV. Make the distance between the lens and candle a little less than the focal length of the lens, and try to find a sharply defined image by moving the screen. You should thus prove that no *real* image is formed in this case. But look from the candle side toward the lens, and observe a sharply defined image beyond. Describe this image in all respects.

e. One can best explain the production of the image in each case by means of a diagram. Four facts enable him to make the construction:

1. The image of a point is its conjugate focus.
2. Two rays diverging from a point represent all the rays from that point.
3. The refraction of the ray which passes through the optic center of a lens may be neglected.
4. A ray parallel to the principal axis goes through the principal focus after refraction.

Thus for Case II., let L (Fig. 184) represent a convex lens, with its principal axis, xx, its optic center, o, and its principal foci, F and F', and let the object be a small arrow, ab, at less

than twice the focal distance from the lens. From the head of the arrow draw two rays, one directly through *o*, neglecting its refraction, and the other, *ai*, parallel to *xx*. The latter is so bent by the lens that it goes on through *F*. These two rays converge and cross each other at *A*, which is the con-

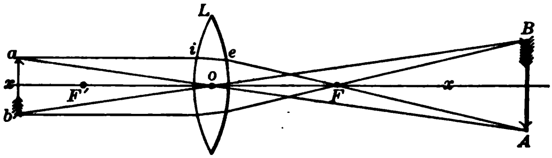


Fig. 184.

jugate focus, or image, of *a*. So, likewise, two rays from the other extremity of the arrow, one through *o*, the other parallel to *xx*, cross at *B*, which is therefore the image of *b*. Since points between *a* and *b* must have images between *A* and *B*, *AB* must be the image of the arrow.

f. The descriptions of images obtained by the use of converging lenses are included in the following summary:

Case I. When a lens is at twice its focal length from an object, a real image is formed at twice the focal length on the other side, inverted and the same size as the object.

Case II. When a lens is between once and twice its focal length from an object, a real image is formed at more than twice the focal length on the other side, inverted and enlarged.

Case III. When a lens is at more than twice its focal length from an object, a real image is formed between once and twice the focal length on the other side, inverted and reduced in size.

Case IV. When a lens is at less than its focal length from an object, a *virtual* image is formed on the same side, erect and enlarged.

157. **Spherical Aberration.**—*a.* The principal focus of a lens is the focus of rays which are not only parallel to the axis but also *near to it.* Those rays which pass through the lens near

its edges are refracted more and cross the axis at a point nearer the lens. This production of different foci of the same pencil of rays by different parts of a lens, is called *spherical aberration*. Thus the rays *a* and *b* (Fig. 185), lying near the principal axis, are refracted through the principal focus, *F*. But the rays *c* and *d* are refracted through *f*. In fact, the deviation increases as the rays lie further from the axis, and their foci are distributed all along between *F* and *f*.

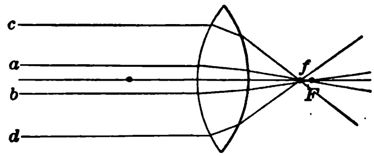


Fig. 185.

b. The effect of spherical aberration is to blur the details of the image. Hence spherical aberration is a serious fault of lenses which are used in optical instruments. It may be corrected partly by using a diaphragm, *i.e.*, a screen with a hole in the center to permit only the light near the axis to enter the lens. The correction is more perfectly accomplished by making the curvature of the lens less near its edges than near the middle. A lens corrected for spherical aberration is said to be *aplanatic*.

158. **Optical Instruments with Lenses.** — *a*. The simple *microscope* is a convex lens used to produce magnified images of small objects. The object is placed at a distance *a little* less than the focal length from the lens (§ 156, *f*, IV.).

Thus in Fig. 186, I., *ot* represents a small object just within the focal distance of the lens, *L*. By tracing the refraction of the rays, as shown, it will be seen that the light from *t* enters the eye as if it came from *t'*, and that from *o*, as if it came from *o'*. The enlarged virtual image, *o't'*, is seen instead of the object, *ot*. This is what is meant when it is said that the object is magnified.

It is well known that an object appears larger when its distance away is less. In fact, we judge the size of a body

by the size of the angle made at the eye by two rays, one from each extremity, called the *visual angle.* If *ot* (Fig. 186, II.) is placed at *nl*, nearer the eye, *E*, it would appear to be as large as *o't'* at the greater distance, because the visual angle *tEo* becomes the larger angle *lEn* or *t'Eo'*. Now a lens magnifies by causing the light to enter the eye as it would enter if the object were brought nearer to it.

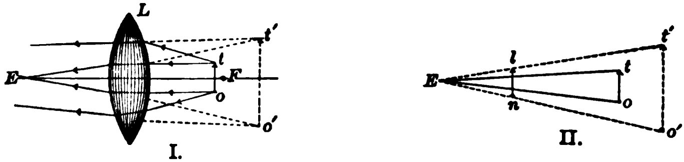


Fig. 186.

b. A minute object can be seen most distinctly when about 10 or 12 inches from the eye; if brought nearer, it will be blurred. Try it. Ten inches is regarded as the *average limit of distinct vision.* What is your limit of distinct vision? So a minute object will appear the largest possible when it is about that distance from the eye. But a lens bends the rays so that they enter the eye as if the object were less than 10 inches away, and still preserves distinctness.

The *magnifying power of a lens is the ratio of the diameter* (or length) *of the image to that of the object.* This is the same as the ratio of the *distance of the image from the lens to that of the object from the lens.* In case of the simple microscope, it is the same as the ratio of 10 inches — the limit of distinct vision — to the focal length of the lens. Thus the magnifying power of a simple microscope, whose focal length is $\frac{1}{2}$ inch, is $10 \div \frac{1}{2} = 20$ diameters. The dot of an *i*, viewed with such an instrument, would appear to be 20 times as wide as it is.

c. The *compound microscope,* in its simplest form, consists of two convex lenses placed at opposite ends of a tube. One lens, *O* (Fig. 187), near which the object is placed, is called

the *objective,* and another, *P,* near which the eye is placed, is called the *eyepiece.* The objective is to form a real and enlarged image ($a'b'$) of the object (§ 156, *f,* II.), and the eyepiece is to produce a virtual and magnified image (AB) of that image (§ 156, *f,* IV.). Notice where the object must be placed; where its image will be; where the eyepiece must be placed with respect to this image.

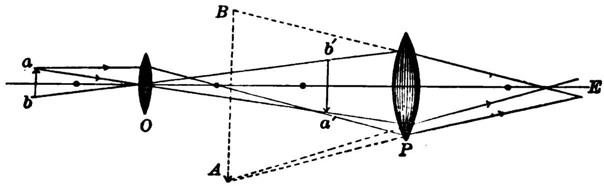


Fig. 187.

d. The *telescope* is an instrument by which to magnify a small image produced near by, of an object so far away that its details are indistinct. If the small image is made by a lens, the instrument is called a *refracting telescope,* or *refractor;* if by a concave mirror, the instrument is called a *reflecting telescope.* In both classes, the small image is magnified by means of a lens.

e. The *astronomical refracting telescope* in its simplest form consists of two convex lenses. The *object glass, O* (Fig. 188), is that which takes the light from the distant body and produces the image, *i;* the *eye glass, E,* is that through which the eye views the magnified image, *I.* The course of the rays may be traced in the figure. The object is at so great a dis-

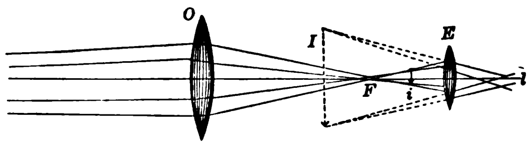


Fig. 188.

tance that the image by the object glass is many times smaller (§ 156, *f*, III.); but this image is at a little less than the focal length from the eye glass (§ 156, *f*, IV.), which, therefore, magnifies it.

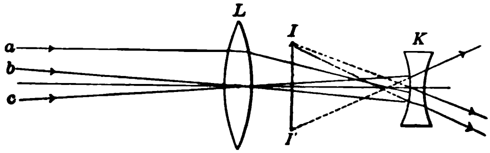


Fig. 189.

f. The image in the astronomical telescope is inverted. When looking at objects on the earth, it is desirable to render the image erect. For this purpose two convex lenses are placed near the eye glass. These form a second real image, which is inverted with respect to the first and erect with respect to the object. This erect image is magnified by the eye glass. The *spyglass* is a telescope of this kind.

g. The *opera glass* consists of two telescopes side by side, one for each eye. An erect image is obtained in each by the use of a concave lens for the eye glass. Rays of light, *a*, *b*, (Fig. 189) from the top of a distant object, after passing the object glass, are received by the concave eye glass, and enter the eye, diverging as if they came from the point *I*, while rays *c*, from the bottom of the object, after refraction diverge as if they came from the point *I'*. Thus an erect image, *II'*, may be obtained.

h. The *optical lantern* is an instrument for projecting magnified images of objects upon a screen. A source of light (*L*, Fig. 190) is inclosed in a dark box. One or more convex lenses, called the *condenser* (*C*), close an opening in the side of the box. The object, which is usually a photograph on glass, is placed in front of this lens, and, finally, another convex lens, *O*, called the *objective*, is placed in front of the object. The condenser collects light from *L*, and illuminates

the object brightly. The objective, placed between once and twice its focal length from the object, gives upon the screen a real, enlarged, and inverted image (§ 156, *f*, II.).

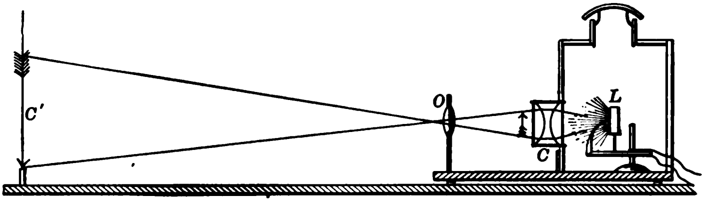


Fig. 190.

i. The *camera* is an instrument to form miniature images of objects, usually on chemically prepared plates. In principle it is a converging lens with the object at a distance greater than twice the focal length. It consists of a box made light tight, and blackened inside in order to be perfectly dark, with a tube (*T*, Fig. 191) in one end, carrying a convex lens, or a combination of lenses, and a sheet of glass at the back, which is the screen to receive the image. This instrument is used chiefly by photographers. Having "focused" the image upon it, the photographer removes the screen. He substitutes the

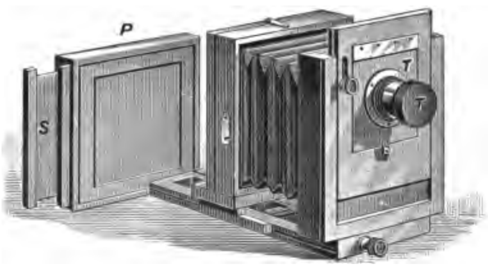


Fig. 191.

plate holder, *P*, and "exposes" the sensitive plate by drawing the slide, *S*.

159. **The Eye.**—*a.* The eye, like the camera, is a light-tight chamber with lens and screen. The arrangement of its parts

may be understood by attentively studying Fig. 192, which represents a vertical section from front to back. The outside wall is a hard, tough membrane called the *sclerotica* (*S*). It is opaque, as seen in the white of the eye, except in front, where a portion is transparent and called the *cornea* (*C*). Lining the walls, except in front, is the *choroid coat* (*K*). In front this membrane stretches across the space behind the cornea, and is called the *iris*. This is the colored part of the eye, and the opening in it is called the *pupil*. Entering the eye from behind is the *optic nerve* (*O*), which branches into a network of fibers. This network (*N*) completely covers the surface of the choroid, and is called the *retina*. Behind the iris is the *crystalline lens* (*L*), which is more convex at the back than in front, made of a stiff, jellylike substance, which increases in density toward the center. The cavity (*V*) behind the lens (*L*) is filled with a transparent, jellylike substance called the *vitreous humor*, and the cavity in front of it is filled with a more limpid fluid called the *aqueous humor*. These three transparent, lens-shaped substances refract the light which comes from objects, and produce images upon the retina (*N*), which are very small, when compared with the objects, and inverted (§ 156, *f*, III.). The energy of the ether waves is expended on the extremities of the nerves located in the retina, and the nerves transmit it to the brain. What work this energy does in the brain we cannot tell, but the mind translates it into the sensation of sight.

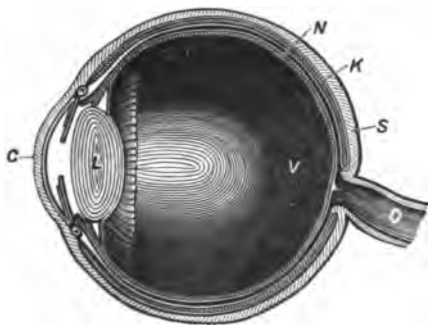


Fig. 192.

b. In order to place the images of all objects sharply upon

the screen, or retina, the crystalline lens is provided with muscles by which it can be made more or less convex. When more convex, its focal length is less, and it is adapted to objects near; when less convex, its focal length is greater, and the images of more distant objects will fall upon the retina. In little more than an instant we can change the focal length of the lens so that an object miles away, or one only a few inches off, will be sharply imaged upon the retina.

c. But many eyes are defective in the power of adjustment to different distances. In some cases the curvature is naturally so great that only near objects can be seen distinctly,—the images of distant objects falling in the vitreous humor in front of the retina. A person with such eyes is *nearsighted.* In other cases the natural curvature of the eye is too small, so that light from a near object is not directed to foci on the retina but further back; only distant objects can be seen distinctly. A person with such eyes is *farsighted.*

Sometimes the curvature of the eye is not perfectly spherical; it is more or less *cylindrical* in one direction or another. In such cases the images on the retina are distorted, being elongated in the direction of the length of the cylinder. Such eyes are said to be *astigmatic.*

These defects are corrected by the use of lenses. Nearsighted people use *concave* glasses to throw the images back upon the retina. Farsighted people use *convex* glasses to bring the image forward to the retina. Astigmatism is corrected by means of *cylindrical* glasses.

DISPERSION OF RADIANT ENERGY—COLOR.

160. **Newton's Experiment.**—*a.* In 1676 Sir Isaac Newton described a memorable experiment, which may be repeated in the following way:

Through a small round hole in a window shutter permit a

slender beam of sunlight to enter a darkened room. Across the sunbeam (*W*, Fig. 193) fix a prism in position to bend the light toward a screen, *S* (Experiment 99). Instead of a round or oval white image of the sun, which would be found at *O* if the prism were not used, there should be seen an oblong band, *vr*, glowing with many colors.

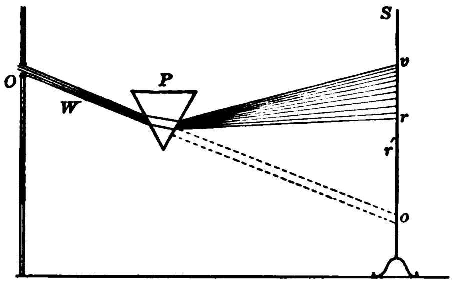


Fig. 193.

b. Newton called this sheet of colors which he obtained from sunlight the *solar spectrum*. He grouped the colors in seven divisions: red, orange, yellow, green, blue, indigo, and violet, in their order, beginning with that which is deviated (§ 153, *a*) least. But these colors are not distinctly separated; they shade insensibly from one to another; in fact, there is a different tint at every point of the spectrum from end to end.

c. Newton's experiment teaches:

1. That the sunlight is a compound of many colors. This is true of all white light.

2. That the different colors have different refrangibilities; red is refracted least and violet most of all.

The decomposition of light, or the separation of rays of different refrangibilities by refraction, is called *dispersion*.

d. According to the wave theory, the difference in refrangibility corresponds to the difference in the wave lengths. The longer waves are not so much retarded (§ 154) by the denser medium, and, consequently, are not so much turned out of their course. The wave lengths have been measured, and that of red light has been found to be about .000076 cm., of violet

light about .000040 cm., while those of other colors lie between these limits.

Experiment 103. — *Object.* To obtain the spectrum of kerosene or gas light.

Mount the following pieces on an optical bench: A card with a hole in its center, about .5 cm. in diameter, bound by rubber bands over the hole in one of the sliders very near one end of the bar; a convex lens with focal length (§ 156, *d*) of about 20 cm., supported by another slider, at about 30 cm. from the card; a screen at the other end of the bar. See that the hole and the center of the lens are adjusted to equal heights. Finally, put a good kerosene lamp, with a flat wick, as near to the card as may be, with its flame edgewise toward the card, and the brightest part of the flame at the same height as the hole. The darker the room the better will the results be.

Now move the lens until a sharp image of the hole is formed on the screen. Fix the prism vertically, very near the lens, on the screen side, with its back toward you. Put another screen in place to receive the refracted light, and *at the same distance as the first* from the prism. Turn the prism on its axis until the colors appear as bright as they can be made.

e. The spectrum obtained from a circular beam of light is not well defined. Its ends are rounded, and its colors are mixed, or impure, because it is really composed of many overlapping spectra. A *pure spectrum* is one whose colors are adjacent, but not overlapping.

To obtain a pure spectrum we must have:

1. A very narrow slit, parallel to the edge of the prism, instead of a wide opening, to admit the light.

2. A lens so placed as to form a clearly defined image on the screen.

3. The prism in position of minimum deviation.

Experiment 104. — *Object.* To show that with a wide opening a spectrum must be made up of overlapping spectra.

With a large needle pierce a card with three or four smooth holes in a line whose length is about equal to the diameter of the hole used in the preceding experiment. Mount this card in front of the flame, with the line of holes horizontal, and proceed as in Experiment 103, except that you put the spectrum screen nearer the prism and gradually move it away.

You should discover that each small beam yields its own spectrum, but that their colors do not coincide but overlap one another. Now imagine the many such small beams in the light which passes through a wide opening, and the cause of mixed colors in the spectrum is evident. Try with the line of holes vertical. Note the difference.

Experiment 105. — *Object.* To obtain a pure and *real* spectrum.

1. Cut a smooth slit, about 1.5 cm. long and about 1.5 mm. wide (*e*, 1) in a card, and bind the card on a slider of the optical bench, with the slit vertical.

2. Mount a convex lens of about 20 cm. focus on another slider; place a screen at the other end of the bar, and the edge of a kerosene lamp flame in front of the slit. Adjust the center of the lens, the center of the slit, and the brightest part of the flame, to equal heights. Then move the lens until the sharpest possible image of the slit is obtained (*e*, 2).

3. Fix the prism vertically, behind the lens, close to it, with its back toward you, or, in general, *with its back in the direction in which you desire to refract the light*, and carry the screen around to receive the

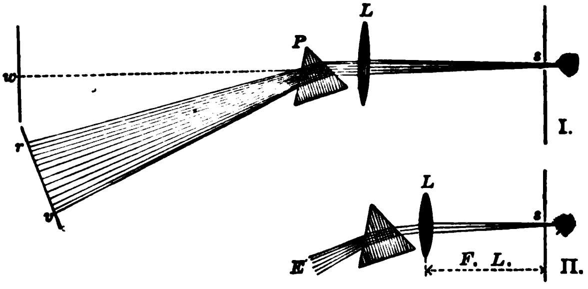


Fig. 194.

spectrum, keeping it the same distance from the lens. Slowly turn the prism on its axis. If the spectrum on the screen moves toward its violet end, or away from *w* (Fig. 194, I.), turn the prism the other way. The spectrum will then move in the direction of the red end for a time, then stop, and, while you turn the prism the same way, the spectrum will reverse its motion and go toward the violet. You can find a position for the prism such that, when it is turned on its axis either way, it will carry the spectrum in the direction of the violet, or make its deviation (§ 153, *a*) greater. That is the *position of minimum deviation* (*e*, 3).

The spectrum should be rectangular in shape, with its ends and edges quite well defined, and its colors purer than those obtained in Experiment 103.

Experiment 106.—*Object.* To obtain a pure but virtual spectrum.

Place the lens at its *focal distance from the slit*, then look directly into the prism (Fig. 194, II.). Move the eye until the colors enter it. The purer spectrum is now seen apparently behind the prism. It is virtual; but its colors are brighter than those of the real spectrum on the screen in Experiment 105. If it is too bright for the eye, reduce the flame, or use a candle, or even the feebler light of a burning match.

161. Explanation of Color.—*a.* Color is a sensation in the eye, which, according to the wave theory, is due to the vibration frequency of the ether waves. Color is analogous to pitch. Air waves of different frequencies are recognized by the ear as sound of different pitches (§ 129, *a*), so ether waves of different frequencies affect the eye as light of different colors.

b. Physicists have computed the wave frequencies—that is, the number of waves per second—that enter the eye, as well as the wave lengths for a great many of the prismatic colors, and the following table gives some of the results. The numbers for red and violet refer to the extreme ends of the spectrum, but the others refer to the central ray of their respective colors.

Color.	Wave Freqüency.	Wave Length.
Red	395 million millions.	.000076 cm.
Orange	503 " "	.000059 "
Yellow	517 " "	.000058 "
Green	570 " "	.000052 "
Blue	635 " "	.000047 "
Indigo	685 " "	.000044 "
Violet	763 " "	.000039 "

c. There are waves in the spectrum which are much longer and have less rapid rate than the red, but they do not affect the eye. They can be detected by a thermometer. In fact, the heat of a sunbeam is largely the energy of these invisible rays. They are called the *ultra-red rays.*

There are waves much shorter, and having more rapid rates

than the violet, but they do not affect the eye. They can be detected by the photographer's plate. In fact, much of the chemical work of the sunbeam is due to the energy of these invisible rays. They are called the *ultra-violet rays.*

Light, considered as that which renders objects visible, is radiant energy which enters the eye in waves whose rates are between 395 and 763 million millions per second. But "there is absolutely no philosophical basis for distinction between the visible and the invisible radiations of the sun, except in the one point of vibration frequency."[1] Their different effects depend on the qualities of the substances on which they fall.

162. **Different Kinds of Spectra.** — *a.* The spectrum of candle light or kerosene light, as in Experiment 103, contains all colors from red to violet, without any break in their continuity. Such spectra are called *continuous spectra.* But there are other spectra which consist of bright-colored lines distinctly separated by dark spaces. Such spectra are called *bright-line spectra.* And there are spectra of a third class, in which the colors are crossed by broad dark bands, or fine dark lines; these are called *absorption spectra.*

Experiment 107. — *Object.* To compare the spectra of light from different sources.

1. Carefully arrange the apparatus to obtain a virtual, pure spectrum, as in Experiment 106. Let the slit be narrow and its *edges smooth.* Let the lens be carefully placed at its focal length from the slit, and the prism in position of minimum deviation. Notice the continuous spectrum — the unbroken gradation of colors from red to violet — in kerosene light.

2. Put the colorless flame of a Bunsen burner in place of the kerosene light. Insert a narrow strip of asbestos, wet with a strong solution of common salt, in the mantle of the flame near its base. The salt will be decomposed, and the incandescent vapor of its sodium will color the flame intensely yellow. You should find the spectrum of this yellow light to consist of a single yellow line, — a yellow image of the slit.

Insert another strip of asbestos, wet with strong solution of strontium chloride. Observe the change produced in the flame; then look for the spectrum of the incandescent strontium vapor.

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[1] *The Sun,* by Charles A. Young, p. 252.

Try also a solution of calcium chloride for the spectrum of incandescent calcium vapor.

3. Obtain once more the continuous spectrum of kerosene light, and then place a strip of colored glass between the lamp and the slit. See whether any of the colors are quite as vivid as before, and note what ones are more completely extinguished. In order to do this more easily, hold the colored glass so that it shall cover only half the length of the slit. Compare the absorption spectra of red, green, and blue glasses. Their colors must not be too dense, else the spectrum will be too faint.

163. **The Spectroscope.** — *a.* The spectroscope is an instrument for the observation of spectra. Its three essential parts are a *collimator*, a *prism*, and a *telescope*. The collimator

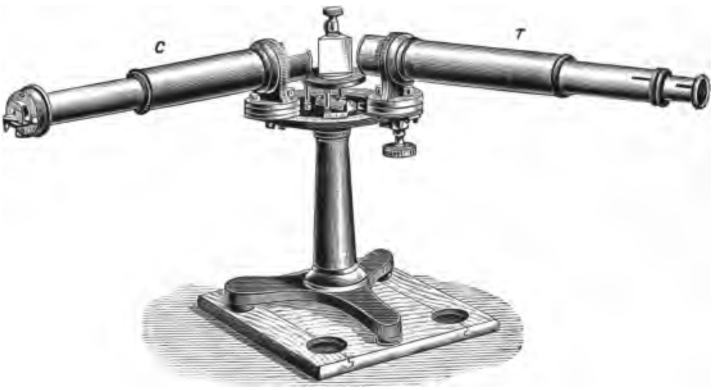

Fig. 195.

(*C*, Fig. 195) is a tube having a slit at one end, and a lens near the other end adjusted to its focal distance from the slit. Its purpose is to render parallel the diverging rays of the narrow beam which comes through the slit (§ 156, *d*). The prism rests upon a circular table in its position of minimum deviation. Its purpose is to disperse the parallel rays from the collimator and produce a pure spectrum. The telescope (*T*) is a small astronomical refractor (§ 158, *e*). Its purpose is to magnify and define the spectrum.

b. When the instrument is so constructed that the spectrum

can be *measured*, it is called a *spectrometer*. There are two ways to make the measurements.

1. The circular table of the instrument is graduated (Fig. 196). The collimator and telescope constantly point to the center of the circle. The former is fixed, while the latter is movable, so that its axis can be brought into line with any part of the spectrum. The distances between different points in the spectrum are measured by the angle through which the telescope swings, and this is read on the graduated circumference.

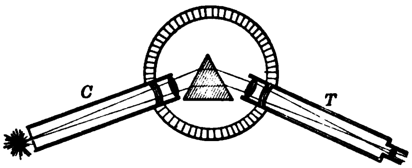

Fig. 196.

2. A third tube (*S*, Fig. 197) is provided, which carries a scale photographed on glass at one end, and at the other a lens adjusted to its focal length from the scale. The scale is illuminated; the rays from it are made parallel by the lens and are reflected from the face of the prism into the telescope. The observer sees a virtual image of the scale lying along the edge of the spectrum.

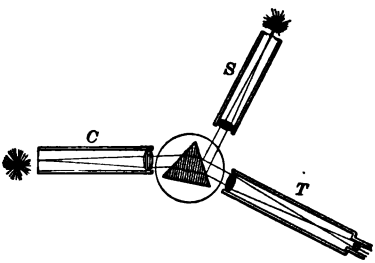

Fig. 197.

164. **The Fraunhofer Lines.**—*a*. The spectroscope shows that the solar spectrum is not a continuous spectrum (§ 162, *a*). Very narrow, dark lines, in great numbers, break the continuity of the colors. These lines are called the *Fraunhofer lines*, in honor of the German optician, Fraunhofer, by whom they were first carefully examined.

b. Fraunhofer designated several of the prominent dark lines by the letters A, B, C, D, E, F, G, H. A is found in the

extreme red end of the spectrum, and H in the violet. Every Fraunhofer line holds a fixed place in the colors. On this account they are very useful as reference marks to locate points in the spectrum precisely.

c. The Fraunhofer lines are produced by absorption. It has been proved that dark bands and dark lines may be produced at will in a spectrum, by causing some of the rays to be absorbed by passing through certain substances. It is therefore inferred that the dark lines in the solar spectrum are due to the absorption of certain rays from the light of the brighter body of the sun in its passage through the vapors which surround it, as our atmosphere surrounds the earth. Each substance in the sun's atmosphere can absorb the same color which it can emit when ignited, very much as one tuning fork can absorb just the same sound which it can yield when vibrated (§ 125, *b*, *c*; § 123, *c*).

165. **Spectrum Analysis.** — *a.* The spectroscope has revealed the following facts in regard to the three classes of spectra (§ 162):

1. Continuous spectra are due to incandescent solids, liquids, or dense vapors.

2. Bright-line spectra are due to incandescent gases and vapors of little density.

3. Dark-line spectra are due to absorption of rays by the vapors or gases through which they are transmitted.

Hence it is possible, with a spectroscope, to learn something of the physical conditions of luminous bodies. For example: The spectra of certain comets consist of bright lines; the inference is that these comets are not solid bodies, but consist of gaseous matter.

b. The spectroscope has also revealed the following facts in regard to light from different incandescent elements:

1. The spectrum of an element which is in the form of an incandescent vapor consists of bright lines.

2. Each element invariably gives the same set of lines when ignited under the same conditions of temperature and pressure.

3. The lines of different elements differ in color and in the places which they hold in the spectrum.

Hence it is possible, with a spectroscope, to learn much about the composition of substances. For example: Sodium is detected by its yellow line, and strontium by its blue and crimson lines (Experiment 107), more readily than by any other means.

c. In the third place, the spectroscope shows that the absorption spectrum of an element consists of dark lines holding exactly the same places that the colored lines of its bright-line spectrum hold. Hence the spectroscope enables the astronomer to learn the composition of the sun and stars. A single example must suffice to illustrate this method of analyzing the sun and stars. A bright-line spectrum of iron and the dark-line solar spectrum are obtained, lying edge to edge, and the observer discovers that certain dark lines of sunlight exactly coincide in position with the lines of the spectrum of iron. The inference follows that iron is one of the constituents of the sun.

166. **Dispersion by Lenses.** — *a.* That a lens decomposes light after the manner of a prism, although less completely, is shown by the following experiment:

Experiment 108. — Admit a beam of sunlight into a darkened room, and use a double convex lens to produce an image of the opening on a screen. The circular image will have a colored border. Hold a small cardboard screen in the refracted pencil, near the lens, and move it gradually toward the principal focus. The circle of light upon it will diminish in size. A place can be found where it is reduced to a small circle of colors with the violet on the inside. But by moving the screen further away the circle of colors will appear with the red on the inside. This shows not only that the lens decomposes the light, but also that the different colors are brought to different foci, that of violet being nearest the lens. The decomposition of light by a lens is called *chromatic aberration.*

b. Chromatic aberration is explained by the accompanying diagram. Trace the rays from *P* as they are refracted and

dispersed by the lens. Rays of light are decomposed in passing through the lens, because the colors are not equally refracted, and the focus for violet is at *v*, while that for red is at *r*.

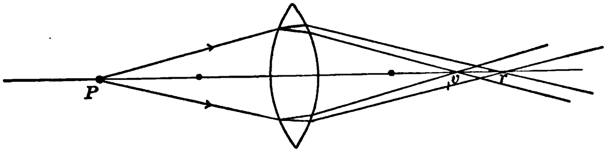

Fig. 198.

c. The effect of chromatic aberration is to give colored fringes to the images produced by lenses. But it is possible to remedy this evil by constructing lenses composed of two kinds of glass. Such lenses are said to be *achromatic*. One form of achromatic lens is shown by Fig. 199.

Fig. 199.

It consists of a double convex lens of crown glass and a concave lens of flint glass. The crown glass bends the rays in one direction, while the flint glass bends them in the other (Fig. 182, 1, 5). Now flint glass has greater dispersive power than crown glass, but about the same refractive power. So a thinner lens of flint glass may neutralize all the dispersion of the crown-glass lens, but only part of the refraction.

167. **The Colors of Bodies.** — *a*. We see objects by the light which comes from them. *The color of a body is really the color of the light which it sends to the eye.* In the case of non-luminous bodies, the light that comes from them is light which they reflect, or light which they transmit. But we have seen that a part of the radiant energy received by any body is arrested by the molecules, and remains in the body as molecular energy. Every molecule, or group of molecules, in a body has its own vibration rate (§ 123, *c*). These rates, and no others, it will absorb from the ether waves. This absorbed energy goes to warm the body, or to produce chemical changes in it.

But other ether waves, those whose frequencies do not correspond to those of any of the molecules or groups of molecules in the body, are not absorbed. They are reflected or transmitted, and by these the object is seen. *The color of an object is, therefore, the color of the light which it rejects.*

b. Some substances, like snow and window glass, absorb all colors equally well, so that the light which they reject contains all colors in the same proportion as that which they receive. In such cases, objects, if opaque, are said to be *white*, and if transparent, are said to be *colorless*. Sometimes the absorption is so complete that the eye is not much affected by the reflected or transmitted light. In this case the object exhibits a darker hue, and in the extreme case it is said to be *black*.

c. But many substances, such as green silk and blue glass, absorb certain colors in preference to others. The absorption is not *general*, but *selective*. The light which comes from such bodies lacks certain colors, or contains them in smaller proportions than does ordinary white light. Such light is described as *colored light*, and the color of such a body is the color of the residue which it does not absorb.

Thus the absorption spectrum of blue glass (§ 162, *a*) shows that the glass absorbs nearly all the red, orange, and yellow rays, and some portions of the other colors, but transmits a large part of the blue, with smaller portions of green, indigo, and violet. Now the color of the glass is a compound color, due to a mixture of those which the glass does not absorb. In this way the colors of all transparent bodies may be explained.

Again, the color of a certain ribbon is scarlet, because the materials of the ribbon absorb all the colors of white light except red and orange. These two colors are reflected in certain proportions — 85 red to 15 orange. They are blended in the eye, and their resultant is scarlet. In a similar way the colors of all opaque bodies may be explained.

d. White light is a compound of all the colors contained in the solar spectrum (§ 160, *b*, *c*). But it is possible to produce light which affects the eye as white light does, by blending two colors only. This may be shown as follows:

Experiment 109. — Let two beams of sunlight enter a darkened room. Fix a piece of orange-colored glass (*o*, Fig. 200) across one, and a piece of blue glass (*b*) across the other. Reflect both beams to a screen, *S*, by two plane mirrors, *m* and *m'*. Two patches of light will be seen on the screen, one orange at *o'*, the other blue at *b'*. By turning one mirror, say *m*, a little, the orange may be thrown upon the blue at *b'*, and where the two patches of light overlap, the screen is neither orange nor blue, but nearly white. Thus the mixing of orange and blue lights produces white. Gelatine films tinted to pure colors are in the market, and may be used for such experiments to advantage.

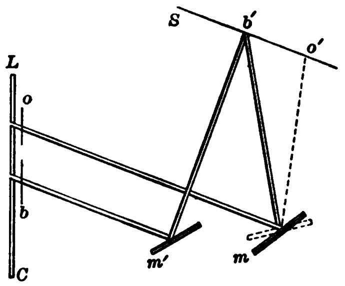

Fig. 200.

Two colors which blend to produce white light are called *complementary colors.* Orange and blue are complementary colors. Red and bluish green are complementary; so are yellow and indigo, yellowish green and violet, green and purple. Ribbons, flowers, or fabrics with complementary colors, if placed side by side, heighten the brilliancy of each other by contrast.

e. But while a mixture of blue and yellow lights is nearly white, a mixture of blue and yellow pigments is green. This difference is due to the fact that when lights are mixed their colors are *combined;* but when pigments are mixed their colors are partly *neutralized* by absorption. Each pigment absorbs a part of the colors from white light, and the color of the mixture is the residue which is not absorbed by either. Thus:

White light consists of	R. O. Y. G. B. I. V.
Blue paint absorbs	R. O. Y.
Yellow paint absorbs	B. I. V.
The residue absorbed by neither . .	G.

168. Colors by Interference. — *a.* In 1801 Thomas Young made the following memorable experiment:

Experiment 110. — He obtained a very small pencil of light through a narrow slit (S, Fig. 201) in the window shutter of a darkened room. In the path of this light he placed a screen (A) in which there were two small pin holes (a and b). In this way he obtained two small pencils of light from the same source, which overlapped each other on another

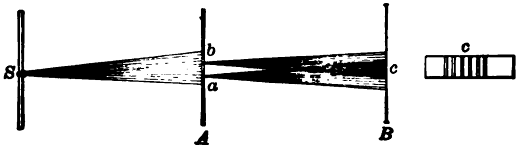

Fig. 201.

screen (B). Instead of a bright patch of light (at c) where the two pencils were thrown together, he observed a series of bands alternately *dark* and *rainbow colored.*

When light of one color was used, the bright bands were that color only. Thus yellow light gave alternate dark and yellow bands. Try it with yellow and blue glass. When either aperture was covered, the bands disappeared; this showed that it was the mutual action of two portions of light that produced them.

b. We have seen (§ 136, *d*) that two sounds may combine to produce alternate sound and silence. Young's experiment showed that two portions of light may combine to produce alternate light and darkness.

If two equal ether waves interfere in like phases, they produce a wave of double amplitude, and, in the eye, this would be a brighter light. If they interfere in opposite phases, they neutralize each other; this would produce darkness. Thus the alternate bands of color and darkness in Young's experiment are produced by the interference of light.

c. The colors of a soap bubble are interference colors. Let B (Fig. 202) represent a section of a bubble. Of course the thickness of the film is very much exaggerated. The film is thinnest at the top, because the viscid fluid gradually sinks

toward the base of the bubble by gravity. At *b* a part of the incident light, *l*, is reflected, and, at *a*, part of that which passes into the film is reflected. These two reflected parts proceed in almost the same direction. Imagine another ray, *l'c*, parallel to *lb*, reaching the bubble at *c*. Its reflected part would exactly coincide with that reflected from *a*, and both would flow together into the eye at *E*. But the light from *la* has gone the distance *bac* farther than the light from *l'c* to reach the eye. So the wave from *la* lags behind that from *l'c* a distance equal to twice the thickness of the film.

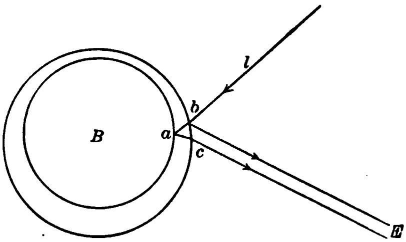

Fig. 202.

Now suppose the thickness of the film at that place is equal to one half the wave length of red light; then the two waves, *b* and *c*, should reach the eye in like phases, but the reflection at *a*, *changes the phase*[1] of the wave *c*, so that they reach the eye in opposite phases and neutralize each other. Thus the red is cut out, and the remaining colors enter the eye. At other places the thickness of the film is one half the wave length of the other colors; these colors are cut out at those places, and the color of the bubble is made up of what are left.

169. **Diffraction.** — *a*. When light of one color is sent through a narrow slit and received upon a screen in a darkened room, that color is seen as a series of bright bands separated by dark spaces. If white light is used, a series of spectra separated by dark spaces is obtained. The action by which these alternate bands of color and darkness are produced is called *diffraction*.

[1] Reflection taking place from the surface of a rarer medium always changes the phase of the wave.

Experiment 111. — *Object.* To illustrate the diffraction of white light by obtaining diffraction spectra.

Apparatus. An optical bench (Fig. 154). A card with a clean-cut slit, between .1 cm. and .2 cm. wide. A piece of glass covered with a film of collodion, with a ***straight line cut through the film*** by means of a needle point. A candle.

Operations. Mount the glass plate, with its transparent line vertical, on an upright slider at one end of the bench, and the candle on the platform slider at the other end. Mount the card, with its slit vertical, on an upright slider near the candle. The two slits and the candle flame must be carefully adjusted to equal heights and in a straight line, and the glass plate would better be placed with its glass side toward the flame. By looking through the line on the glass, the slit in the card, illuminated by the candle, may be seen between two rows of spectra which stretch away to the right and left. Carefully observe the order of the colors in the spectra on the opposite sides of the slit. Interpose colored glasses, and carefully observe the results.

b. Diffraction bands are due to interference. Suppose red light to start from *R* (Fig. 203) and pass through a narrow slit, *ab*; it will go straight forward to *W*. But the bands are not

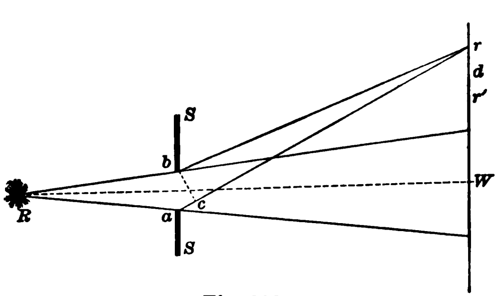

Fig. 203.

due at all to these direct rays. They are due to rays, *ar* and *br*, that start afresh from the edges of the slit. As the slit is very narrow, these rays go in nearly the same direction and interfere at *r*.

Draw *bc* perpendicular to *ar*. It is evident that the light from *a* goes the distance *ac* farther than that from *b* to reach *r*. If *ac* is any even number of $\frac{1}{2}$ wave lengths of red light, the

interference will be in like phases and produce a bright band; but if *ac* is an odd number of ½ wave lengths, the light interferes to produce darkness (§ 135, *c*). Now *ac* will be longer as *r* is farther from *W*. At *r'* it may be an even number of ½ wave lengths; at *d*, an odd number, and at *r*, an even number again, and so on, thus producing the alternate bright and dark bands.

The same explanation applies to each color of white light, but *ac* is shorter for other colors than for red, and hence the bands of other colors lie nearer to *W*.

c. A *diffraction grating* consists of many parallel lines ruled very close together on a surface of glass or metal. These lines on glass are opaque, while the spaces between them are transparent. The grating is, therefore, equivalent to a large number of slits side by side. A thousand lines to the centimeter, or 2500 to the inch, is not a very fine grating. Rowland's gratings on metal contain from 10,000 to 20,000 lines to the inch. The effect of the increase in the number and fineness of the lines is to increase the separation of the bands.

There is no overlapping of colors in the diffraction spectrum, and the place of each color is fixed by the wave length. In these respects it differs from the prismatic spectra.

POLARIZATION OF RADIANT ENERGY.

170. **Double Refraction.** — *a.* Certain transparent crystals not only refract light, but divide each ray into two parts, which they transmit separately. This division of a beam by refraction is called *double refraction.*

b. Thus *IS* (Fig. 204) represents a section of a crystal of Iceland spar, and *A* a small beam of light in a darkened room. *A* is broken into two beams, *o* and *e*,[1] one bent more than the

[1] This is true of all rays, except such as enter the crystal in the *direction* of the dotted lines, a direction *which is equally inclined to the edges of the obtuse angle.* This direction is called the "optic axis" of the crystal; rays in that direction are not doubled.

other. When they emerge, they are bent just as much the other way (Experiment 98), and pass on separately. If they fall on a screen, *N*, two images of the opening, *w*, will be seen there. If they enter the eye, two virtual images of the

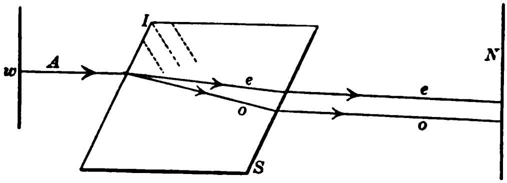

Fig. 204.

opening will be seen instead of the opening itself. Everything seen through the crystal appears double. The distance between the two images depends on the thickness of the crystal; in small crystals the images overlap.

c. Of the two beams obtained by double refraction, one, *o*, is called the *ordinary beam*, because it follows the common law of refraction (§ 152, *d*); but the other, *e*, is called the *extraordinary beam*, because it does not follow that law.

d. A curious change is wrought in the light by double refraction. We know that a beam of common light is reflected by glass without any regard to the position of the reflecting sur-

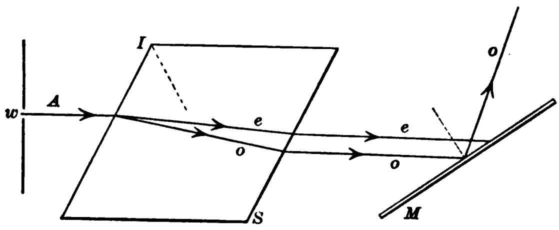

Fig. 205.

face. But this is not the case with doubly refracted light. If a plate of unsilvered mirror glass, *M*, is held across the two beams, as shown in Fig. 205, so that the angle of incidence

is $54\frac{1}{2}°$, the ordinary beam will be reflected, but the extraordinary will not. Let the glass be turned over a little around the beam as an axis, and the extraordinary beam will be reflected faintly. Continue to turn the glass, and the extraordinary beam will grow brighter while the ordinary beam will grow fainter until, at 90° over, the former is reflected in full brilliancy, and the latter is extinguished. Both beams cannot be reflected perfectly in the same plane. Their planes of best reflection are at right angles. Light in this condition is said to be *polarized.*

171. **Polarization.** — *a.* Polarized light is light that has been so changed that its reflection and transmission vary with the position of the surface which reflects it, or of the medium which transmits it.

b. Light is polarized not only by double refraction, but by reflection also. *A* (Fig. 206) represents a plate of unsilvered glass, *l*, a beam of light whose angle of incidence is $54\frac{1}{2}°$. At this angle a small part of the beam is reflected; the larger part is transmitted. But the reflected part, *p*, is completely polarized. That *p* is polarized would be proved by testing it with another glass (*M*, Fig. 205). It would be reflected fully in one plane, but not in another perpendicular to the first.

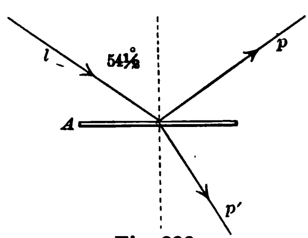

Fig. 206.

As to the refracted beam, *p′*, it contains just the same quantity of polarized light as *p*, but this is mixed with a larger quantity that is not polarized. At any other than this particular angle of incidence, $54\frac{1}{2}°$, the reflected beam, *p*, is also only partly polarized.

Water, polished wood, and other *non-metallic* substances polarize light by reflection. The angle of incidence, at which polarization is complete, is called the *polarizing angle.*

c. Polarized light cannot be detected by the unaided eye. It is studied by means of an instrument consisting of two parts,—one to polarize the light, and the other to show that the light is polarized. The former is the *polarizer;* the latter is the *analyzer;* and the two together constitute a *polariscope.* Thus in Fig. 205, the Iceland spar is a polarizer, and the mirror is an analyzer.

The usual way to test light for polarization consists in putting the eye to the analyzer, and observing whether any change in brightness or color occurs when the analyzer is rotated.

d. The wave theory offers the only satisfactory explanation of polarization. According to this theory, polarization is a change in the *form* of the ether waves. Ether waves are transverse waves (§ 113). In this respect they resemble water waves. But instead of the vibrations being in one plane, as in a water wave, *the ether vibrations are in all possible planes* across the path of the wave. Thus if we could see the ether, and should look at a ray endwise, we should expect to see something like that represented by *A* (Fig. 207),—the ether vibrations taking place in all planes perpendicular to the path of the ray.

What a polarizer does is to reduce all these vibrations to two sets, which take place in planes at right angles to each

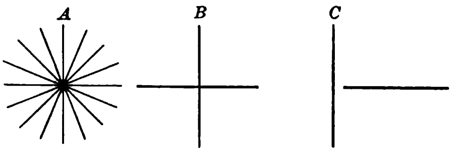

Fig. 207.

other, as represented by *B* (Fig. 207), and at the same time to separate the two sets, as shown by *C*, so that they take different paths. In this way the ordinary and extraordinary beams are produced.

Then, because the ether vibrations in the two beams take place each in one plane, and with the two planes at right angles to each other, they can be reflected by a mirror, or transmitted by a doubly refracting substance, each in one plane only.

e. But the phenomena of polarization are so numerous and complex that a full description of them — of their applications and their explanations — should be sought for in larger treatises on physics or special works on light.

X. ELECTRICITY.

ELECTRIC ATTRACTION AND REPULSION.

172. **Electrification.** — *a.* The meaning of the term *electrification* is illustrated by the following experiment:

Experiment 112.[1] — 1. Place upon the table some light bodies, such as pith balls, bits of cotton wool, or bran, and touch them with a *dry* ebonite rod. They will not be affected. But rub the ebonite briskly with *dry* flannel or fur, and then bring it over the light bodies; they will be attracted to the rod (Fig. 208), and, on touching it, they are quite likely to be repelled. Let the rod lie upon the table; it will be found to lose its power to affect the light bodies, slowly if the atmosphere is dry, quickly if it is moist.

Fig. 208.

2. In order better to show the repulsion, suspend a pith ball by a silk thread from a glass support. Briskly rub the ebonite; bring it near the ball. The ball should fly against the rod (Fig. 209), but, after brief contact, it should fly away again. If the rod is left upon the table for some time, it will no longer repel the ball.

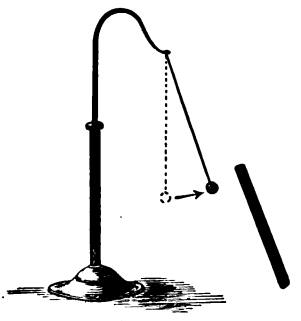

Fig. 209.

So long as the rod has power to attract or to repel light bodies, it is said to be *electrified*.

[1] Experiments in static electricity succeed best in cold, dry weather, and all apparatus should be thoroughly clean from dust and made dry just before using. A moist atmosphere and dirty apparatus are fatal.

b. Electrification is that temporary condition of a body in which it attracts or repels other bodies in its vicinity.

It has been found that *all bodies can be electrified by friction.* But in many cases the return to the natural condition is so prompt that the electrification is not manifest unless special precautions are taken. Metallic bodies, if held in the hand and rubbed, will show no sign of electrification; but it is because the electrification is neutralized by the hand as fast as it is produced. Prevent this, and electrification can be shown, as in the following experiment:

Experiment 113. — Select a *smooth* rod of metal, with *rounded ends.* Stretch a piece of rubber tubing over the end which is to be held in the hand. Rub the rod briskly with fur, without touching it with the fingers, and then present it to the suspended pith ball (Fig. 209).

c. A body may become electrified by contact with one which is already electrified. That the pith ball, after touching the electrified ebonite (Experiment 112, 2), is itself electrified, may be shown as follows:

Experiment 114. — Hang another pith ball beside the first from the same support. Bring the rubbed ebonite near the two. Observe that both are first attracted and then repelled. Remove the ebonite, and observe that *the pith balls repel each other.*

d. But two electrified bodies do not always repel each other. That they sometimes attract each other is shown as follows:

Experiment 115. — Suspend the ebonite rod as follows: Bend up about an inch at each end of a wire about six inches long and then bend the wire at its middle point so as to bring the two hooks about two inches apart and parallel. Hang this double hook by means of a silk thread from a support (Fig. 91). The electrified rod is to be placed horizontally in the hooks. Then bring near the electrified end:

1. Another electrified ebonite rod.
2. An electrified glass rod.

e. Bodies which have been electrified by contact with ebonite which has been rubbed with flannel will be *repelled by the ebonite,* but will, invariably, be *attracted by glass* which has

been electrified with silk. This shows that the electrification of the ebonite is not of the same kind as that of the glass. To distinguish these two kinds of electrification, that of the glass is said to be *positive*, and that of the ebonite *negative*. The signs + and − are used to represent them.[1]

f. The results of all experiments on the attraction and repulsion of electrified bodies may be summed up as follows: *Two bodies having the same kind of electrification, both positive or both negative, repel each other; but two bodies having different kinds of electrification, one positive and the other negative, attract each other.*

g. Electrification is a measurable quantity. The *unit* of charge may be illustrated as follows: Suppose two small balls, a and b (Fig. 210), to be 1 cm. apart. Let them be equally electrified, either positively or negatively, so that they repel each other with a force of one dyne (§ 12, c). The quantity of electrification in each ball is the *unit* charge. It is called the *C. G. S. electrostatic unit.*

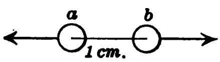

Fig. 210.

h. When the electric force is *measured*, it is found to obey the law of inverse squares. *The attraction of unlike, and the repulsion of like, charges vary inversely as the square of the distance between them* (§ 51, d). They also vary directly as the product of the two charges. In fact, electric forces and gravitation obey the same laws. (See also § 142, b.)

Let there be m units of positive charge on one body, and n units of positive charge on another, and let the distance between them be d centimeters. Then if f stand for the magnitude of their repulsion,

$$f = \frac{m \times n}{d^2}.$$

[1] These are mere names and symbols. + electrification does not mean *more* electrification, nor does − electrification mean *less*. The former means electrification like that of glass when rubbed with silk, and the latter means electrification like that of ebonite when rubbed with flannel. They designate the different *kinds* without regard to *quantity*.

Thus suppose A charged positively with 4 units and B positively with 6 units, at a distance apart of 2 cm.; then their repulsion would be $f = \frac{+4 \times +6}{2^2} = +6$; dynes. Again, suppose the charges were $+4$ and -6 units; then

$$f = \frac{+4 \times -6}{2^2} = -6, \text{ dynes.}$$

The negative sign of the value of f denotes attraction, and the positive denotes repulsion.

173. **Electric Force is Ether-Stress.** — *a.* The motions of electrified bodies, which seem to be due to the mutual attraction and repulsion of the bodies themselves, is really due to a stress in the ether between them. The action is analogous to that in the following experiment:

Experiment 116. — L and C (Fig. 211) represent two smooth blocks on a table and bound together by a rubber cord. Grasp one in each hand and separate them to L' and C'. By this *work* the elastic cord is stretched, or strained (§ 22, *c*). Release the blocks, and the cord, recovering from the strain, will pull the blocks together.

Fig. 211.

The ether is an elastic medium. Let two bodies be oppositely electrified and then separated. By this *work* the ether is supposed to be strained. If now the bodies are free to move, the ether, recovering from the strain, will pull the two bodies together. Since the medium is invisible, the bodies appear to pull each other.

b. The space around an electrified body, through which the influence of the charge extends, is called an *electric field.* A light body, placed in contact with a positively charged body, will move across this field to the negatively charged body on the other side. But its path is not always a straight line. Nor yet is it accidental. The light body ***will start in a line perpendicular to the surface of the positively charged body, and it***

will reach the other side of the field in a line perpendicular to the surface of the negatively charged body. A few of the paths it may take, in the field of two spheres, are represented below.

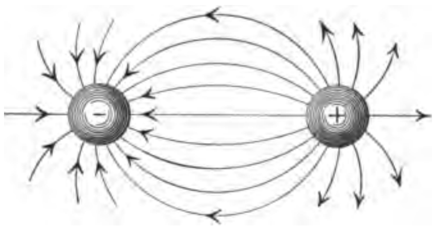

Fig. 212.

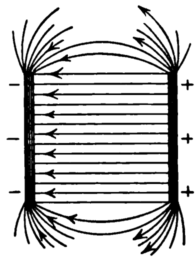

Fig. 213.

The paths cannot be straight lines (Fig. 213) if the surfaces of the electrified bodies are not *parallel* (Fig. 212).

The *directions*, in which a charge is impelled across an electric field, are called *lines of force*.

174. **Electrification and Electricity.** — *a.* Electrification is a kind of potential energy (§ 17, *e*). Thus it is proved that when glass is touched with silk the conditions of both are changed, so that they are held together by a certain amount of force. If they are pulled apart, the energy spent in separating them remains as electrification, positive in the glass and negative in the silk. In general, two dissimilar substances are thrown into opposite electrical conditions, simply by contact, and attract each other. Some amount of work must be done to separate them, and the energy spent in pulling them apart is converted into electrification.

Friction causes repeated contact and separation over large areas of the two bodies, and so much of the energy as is used simply to make the separations becomes electrification.

b. In order to explain why simple contact of two things puts them into opposite conditions, it is assumed that something exists in or around their molecules, which is transferred

from one body to the other. It is called *electricity*. What electricity really is, has not yet been fully revealed. Many believe it to be identical with the ether.

Electricity and electrification are, therefore, two very different things. Electrification is a kind of potential energy. Electricity is not energy at all. We must be content to say, for the present, that electricity is that which is transferred from one body to another in the process of electrifying them.

175. **Conduction.** — *a*. Suppose one metallic ball, *A* (Fig. 214), supported on a glass standard, to have been electrified by contact with glass which has been rubbed with silk; *the electrification spreads* from the place of contact all over the surface. Suppose another ball, *B*, also supported by a glass standard, be brought to touch *A*; the electrification of *A* will be found to spread all over its surface likewise. *A* loses just what *B* gains. Electrification spreads over the metallic surfaces readily. If *B* were a glass ball, it would take almost none at all from *A*. Electrification spreads very freely over many substances, but with extreme difficulty over many others. Make the following experiment to test this:

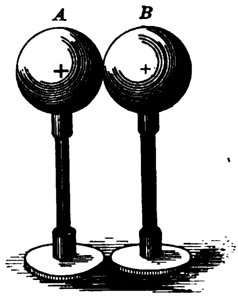

Fig. 214.

Experiment 117. — In Fig. 215, *b* represents a ball of metal,[1] supported by a dry glass flask, with a pith ball hanging in contact with it. *w* represents a slender wire, which may have any length within the range of the table. One end is in contact with the ball, and the other is wound around a glass support, *t*. Rub an ebonite rod, *l*, with fur, or a glass rod with silk, and then draw it over the coil of wire on the tube at *t*. The pith ball should fly away from *b*. The motion of the pith ball shows that *b* is electrified. The electrification must have gone from *l* to *b* over the wire *w*.

[1] A polished brass door knob may be used. Or a wooden ball covered with gold leaf or tin foil, and perfectly smooth, will do as well.

Touch *b* with the finger; the pith ball instantly returns, showing that *b* is no longer electrified; its electrification was transferred by the person to the floor, and thence to earth.

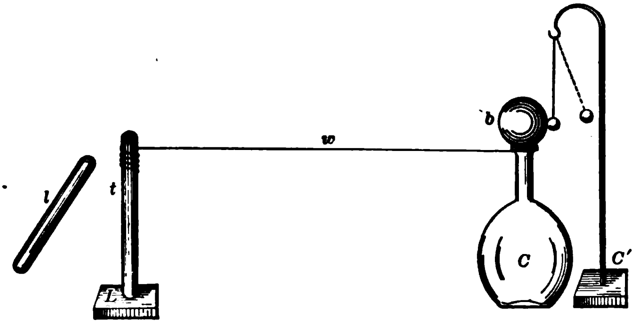

Fig. 215.

Put a silk thread in place of the wire, and bring the electrified rod in contact with the silk at *t*. No motion of the pith ball occurs, which shows that no electrification is transferred by the silk.

b. All metals and many other substances transfer electrification from electrified bodies, as did the wire *w*; but India rubber, dry glass, porcelain, paraffin, dry air, and many other substances resemble silk in being unable to transfer electrification except in so slight a degree as to be nearly or quite imperceptible. Substances which transfer electrification freely are called *conductors*. Substances, like silk and dry air, that offer great resistance to the spread of electrification over them are called *non-conductors*, or *insulators*, or *dielectrics*. But *all* bodies offer more or less resistance to the passage; conduction is a matter of degree only.

c. We now see why the rod of metal (§ 172, *b*) could not be electrified by friction without taking the precaution to cover the end with rubber. The electrification given to it by friction is spread over its entire surface, because it is a conductor, and the hand would carry it away for the same reason; but the rubber is an *insulator*, and prevents its escape to the earth through the person.

In order to electrify a conductor, it must be kept from contact with other conductors. A body which is nowhere in contact with a conductor is said to be *insulated.*

d. When a body is electrified, positively or negatively, it is said to be *charged.* Thus ebonite and glass in preceding experiments have been *charged by friction.* The pith balls used have been *charged by contact* with electrified bodies. The ball, *b* (Fig. 215), was *charged by conduction* through the wire, *w,* from the electrified or charged ebonite.

When a charged body loses its charge, it is said to be *discharged.* Thus when the electrified ball, *b,* was touched with the finger, it ceased to be electrified; it was discharged. Good conductors will be instantly discharged when touched by the hand or any other conductor leading to the earth. Poor conductors, like glass, may be discharged by passing them quickly through a flame; the hot gases carry off the charge.

176. **Electroscopes.** — *a.* An electroscope is an instrument for detecting electrical charges and identifying them as positive or negative.

A pith ball hung by fine silk fiber from a glass support (Fig. 215) is a simple electroscope. It *detects* the charge by moving toward or away from the charged body. It may be used to *identify* the charge as + or −, as follows: Charge the ball by contact with electrified glass or ebonite, so that the sign of its charge *is known.* If charged from ebonite, for example, its charge is negative. Then bring it near the body whose charge is unknown. If it be attracted, that charge is positive; but if it be repelled, that charge is negative (§ 172, *f*).

b. The *gold-leaf electroscope* consists of two narrow strips of gold leaf, — or aluminum leaf, which is lighter, — hung side by side (Fig. 216) from the end of a brass rod, which passes through the cap of a glass jar or the rubber stopper of a flask. The outer end of the rod carries a brass ball. A charge may be *detected* by touching (*without rubbing*) the ball with the sus-

pected body; for if there be electrification, it will be conducted (§ 175, *b*) down to the leaves, and they, being electrified the same way, must repel each other and diverge, as shown in the figure.

To *identify* a charge, let the electroscope be charged with a known kind, and then let the unknown charge be presented to the knob. Thus suppose we rub a piece of sealing wax with flannel, and desire to know whether it is electrified positively or negatively. First charge the electroscope by touching the knob, without rubbing it, with a slightly electrified ebonite rod. The leaves are electrified negatively and fly apart. If, then, the rubbed sealing wax be brought from considerable distance toward the knob, the leaves will diverge more, showing that the charge on the sealing wax is also negative (§ 177, *a*). On the slow approach of an oppositely charged body, the leaves will fall together.[1]

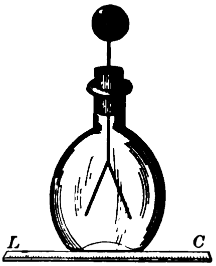

Fig. 216.

Experiment 118. — *Object.* To ascertain whether the rubber, as well as the body which is rubbed, is electrified.

To do this, the rubber should be insulated (§ 175, *c*) from the hand. If glass is to be rubbed with silk, proceed as follows: Roll a strip of silk around a glass tube about the size of the glass rod to be rubbed, so that the silk tube formed shall project beyond the end, and bind it on with thread. Insert the end of the glass rod into the silk tube, and turn it around briskly. Withdraw the rod, and present the silk to an electroscope charged by ebonite. If the electroscope shows repulsion, the silk is electrified, and its electrification is negative. If the electroscope shows attraction, the silk is probably electrified positively, but possibly not, because a neutral body will attract one which is electrified. *Repulsion is the sure test,* and if attraction occurs in any case, the electroscope should be charged again with the other kind, in order that repulsion may occur.

[1] If the body be highly charged and quickly brought up to the knob, the leaves will first collapse and then diverge, and the collapse may be so transient as not to be easily detected. Hence the *slow* approach from a distance is important.

c. One kind of electrification can never be produced without the other. *Exactly equal quantities of positive and negative electrification are always developed at the same time,* one on each of the two bodies which are rubbed together.

Experiment 119. — *Object.* To detect and identify the electrification produced by the friction of different materials.

Ebonite, glass, India rubber, sealing wax, paraffin, sulphur, dry wood, varnished wood, metals (insulated), catskin or other fur, silk, flannel, cotton, and brown paper are suitable substances to test.

First of all, charge the electroscope by contact with ebonite electrified by fur, or with glass electrified by silk, and then recharge with the other kind if, in any case, attraction occurs (Experiment 118). Tabulate the observations in the following form:

Electroscope charged by	Name of Substance.	Name of Rubber.	Behavior of the Ball (or Leaves).	Electrification. +	Electrification. −
Ebonite.	Sealing wax.	Flannel.	Repelled.		—
——	——	——	——		
——	——	——	——		

Remember that everything in use should be *dry,* and that a moist atmosphere discharges an electrified body rapidly.

ELECTRIFICATION BY INDUCTION.

177. **Electrification by Induction.** — *a.* While an electrified body is still some distance away from an uncharged gold-leaf electroscope, the leaves diverge. This shows that the influence of a charged body may electrify another body at a distance. It is proved that the air has nothing to do with this effect. It is an action in the ether, and is called *induction.*

Experiment 120. — *Object.* To produce electrification by induction, and to identify the kind of electrification produced.

Apparatus. The body to be electrified should be a smooth, insulated conductor with rounded ends. It may consist of a large brass wire with its ends bent into loops, and smoothly soldered. It may be supported on a glass vessel, *C* (Fig. 217). A pith-ball electroscope, *C′*; an ebonite rod, *L,* and fur with which to electrify it, are also needed.

Manipulation. Place the pith ball in contact with one end of the conductor. Bring a highly excited rod, *L*, toward the other end, but not too near, because the electricity on *L* will actually *break its way through* a short distance in the medium to reach the conductor. Feeble but sharp snaps are heard when this occurs. While *L* is too far from *c* to discharge its electricity upon it, the pith ball should be repelled, showing that *bc* is electrified. Then take *L* away. *p* will return to *b*, showing that *the electrification by induction lasts only while the inducing charge is near.*

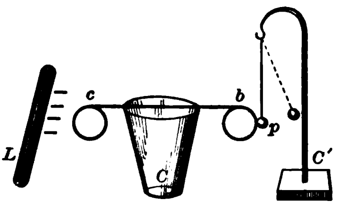

Fig. 217.

The electrical condition of the conductor may be determined as follows: Charge the ball *p* (Fig. 217) by contact with silk-rubbed glass. Then while the electrified rod is near *c*, bring *p* slowly toward *b*. Its motion should show that *b* is negative. Recharge *p*, by contact with fur-rubbed ebonite, and present it to *b*. Its motion should again show that *b* is negative. While *L* is still charged and *p* is negative, bring the latter near to *c*; it will be repelled by *L*, but it should be attracted by *c*, showing that while *b* is negative, *c* is positive.

b. Whenever electrification by induction occurs, both kinds are produced at once on the conductor. *That which is like the inducing charge is on the most distant part of the conductor,* as if the electricity were trying to escape. *That which is unlike the inducing charge is on the nearest part of the conductor,* as if the electricity were trying to reach the inducing body.

c. Induction always precedes attraction. When, for example, a pith ball is brought near to the electrified ebonite, the far side of the ball becomes negative and the near side becomes positive. The negative ebonite then attracts the near side of the ball and repels the far side. But the attraction is stronger than the repulsion because the distance from the ebonite to the positive part of the ball is less than to the negative part.

Experiment 121. — *Object.* To charge a brass ball or other conductor with only one kind of electrification by induction.

Insulate the ball by mounting it upon the mouth of a dry glass flask. Bring a fur-rubbed rod of ebonite near the ball, and touch the ball

momentarily with the finger. Then take the rod away, and prove that the ball is charged positively by testing it with an electroscope.

If the inducing body is a glass rod rubbed with silk, in what condition is the brass ball when charged by induction? Test the truth of your answer by experiment.

d. If an insulated conductor could be divided at its center, and its parts separated while under the influence of a charged body, in what electrical condition would the two parts be?

Find an answer to this question in paragraph *b*, and test your inference by the following experiment:

Experiment 122.—*A* and *B* (Fig. 218) represent two insulated wires, with knobs or rings (§ 175, *c*) end to end, making one continuous conductor, which may be separated into two by moving their supports. *l* represents an ebonite rod, and *p* an electroscope. Electrify *l* by friction, and, while holding it near to *A*, separate *B* from *A*. Then test the electrification of both ends of each, as in Experiment 120.

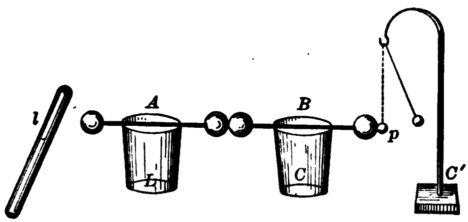

Fig. 218.

Experiment 123. — *Object.* To charge a gold-leaf electroscope with only one kind of electrification by induction.

Bring electrified ebonite toward the knob, and, while the leaves diverge, touch the knob momentarily with the finger. Then remove the ebonite. Prove, by test with a glass rod, that the charge of the knob and leaves is positive. Describe all the motions of the leaves in the experiment, and explain them.

178. **Electrical Machines.** — *a.* Electrical machines are instruments by which insulated conductors may be electrified to a high degree. In the earliest forms the electrification was obtained by friction. The *frictional machine* at first consisted of a globe of sulphur, or of glass, mounted on an axle, so that it could be rotated while pressed by the hand, or a cushion of

leather, for a rubber. Afterward a glass cylinder was used instead of a globe. In the latest forms a circular plate of glass is used, and the electrification produced by the cushion on the rotating plate is continually imparted to an insulated conductor. But frictional machines are now seldom used.

b. In modern machines the electrification is obtained by *induction* (§ 177, *a*). We have seen how an insulated conductor may be charged with one kind of electrification without the other by induction (Experiment 121). Let us now see how the charge may be increased.

A and *B* (Fig. 219) represent two stationary insulated conductors, *A* having a small − charge, and *B* a small + charge. *c* represents a small insulated conductor, which is carried around the circle in the direction shown by arrows, and momentarily *touches* *A* and *B* in each revolution. *L* and *C* represent two conductors extending from the insulated conductors *N* and *P*.

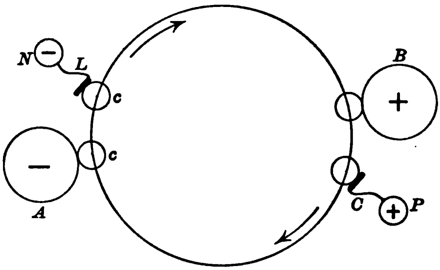

Fig. 219.

As the little carrier ball, *c*, touches the − *A*, it receives a − charge. As *c* recedes from the − *A*, its − charge is repelled, and the side toward *A* becomes + by induction. The repelled negative electrification is taken off by a conductor, *L*, which leads it to an insulated conductor, *N*, wherein it is stored, and *c* goes on with a + charge.

On approaching + *B*, mutual repulsion of like, and attraction of unlike kinds occur.

On contact, the two bodies share their + charges. As *c* recedes from the + *B*, its + charge is repelled and the side toward *B* becomes negative by induction.

On touching the conductor, C, the + charge of c, being repelled by the + of B, passes off to the insulated conductor, P, wherein it is stored, while c goes on with a − charge.

On momentarily touching the $-A$ again, the charges of A and c will be equalized, and as c recedes from $-A$, its − charge is repelled, while the side toward $-A$ becomes + by induction.

On touching L, the repelled − of c passes to N, and c goes on with a + charge.

The same set of actions is repeated during every revolution of the little ball, so that the electrifications of A and B are increased, and that which is stored in N and P becomes greater until these conductors can hold no more.

There are many forms of *induction machines* to produce electrification of high degree by the action illustrated by the foregoing ideal case. They are also called *influence machines.* Among them are the Holtz machine, the Toepler machine, and the Wimshurst machine. But the details of their construction and of their action are complex, and for these the student may consult larger works on physics.[1]

179. **Distribution of Charges on Bodies.** — *a.* When a non-conductor, such as glass or ebonite, is excited by friction, its electrification is confined to the part which is rubbed; but if a conductor receives a charge at any one point, the electrification instantly spreads to all parts of its surface.

b. The charge of an insulated conductor does not penetrate its substance, but resides on the surface only. This seems to be proved by experiments with hollow conductors, the inside surface of which cannot be charged. It is proved also by the fact that the inside material of the conductor is of no consequence. So long as it is of the same shape and size, the conductor may be a solid piece of metal, or it may be hollow, or

[1] See Thompson's *Electricity and Magnetism;* Perkins's *Outlines of Electricity and Magnetism.*

it may be made of wood, or of glass, with a thin covering of gilt or tin foil, and the same charge will be received, and distributed over its surface in the same way.

An electroscope when put inside a metallic cage will show no sign of electrification even when the cage is charged to its utmost capacity. Faraday made a cubical chamber measuring 12 feet each way, with a wooden framework, and walls consisting of a network of copper wire filled in with paper and covered with tin foil. It was insulated and charged by a powerful electric machine. Taking his sensitive electroscopes, he entered this charged chamber, and although electric sparks were leaping from all parts of its outside surface, the instruments were not affected in the least degree. Even a cage of wire gauze will protect anything within it from the influence of electrified bodies outside.

Experiment 124. — *Object.* To compare the electrification at different points on the surface of a charged insulated conductor.

Besides the insulated conductor, a proof plane and a gold-leaf electroscope are needed. A proof plane is a small disk of metal with an insulating handle (Fig. 220). A bronze cent, or better, a disk of tinsel, which is less massive, cemented to the end of a glass rod or an ebonite penholder with wax, answers every purpose. Insulate the conductor, *A* or *B*; see that no other conductors are near it; charge it by repeated contact with electrified ebonite. Then place the proof plane first upon the surface of the conductor, and then upon the knob of the electroscope. The proof plane will receive a charge from the conductor; transfer it to the electroscope, and the amount of divergence of the leaves will be greater or less according to the amount of electrification on the conductor at the place touched by the proof plane.

Fig. 220.

One of the conductors should be a polished metallic, or metal-covered, ball (*A*, Fig. 221). Touch it with the proof plane, carry the charge to the electroscope, and note the divergence. Then discharge both electroscope and proof plane. Touch a different place on the sphere with the proof plane, and again notice the divergence of the leaves. Repeat until all parts of the surface have been tested. Judge whether the electrification was equal everywhere.

Another conductor, *B*, should be oblong, or better, egg-shaped, with rounded ends (Fig. 221). The looped wire (Fig. 217) may be used.

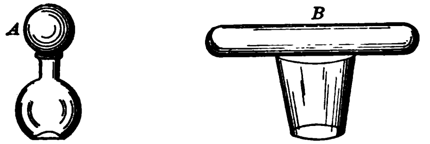

Fig. 221.

c. It has been proved by experiments that the shape of the conductor decides the distribution of a charge upon its surface. On a sphere the electrification is uniformly distributed. On an elongated conductor it is greater at the ends than in the middle. On a flat disk it is greater all around the edge than in the center. On a cone it is greatest at the apex, and if a body terminates in a sharp point, the electrification there is *very much* greater than elsewhere.

d. The term *electric density* denotes the amount of electrification at any point of a surface. Thus, in a general way, we say that the electric density at the ends of an oblong conductor is greater than at its middle part. The precise meaning of electric density, however, is this: *The number of units of electrification per square centimeter or per square inch of surface.*

e. If two insulated spheres of the same size are brought into contact, the total charge on both will be redivided so that each will have one half of the whole. Thus let *A* and *B*

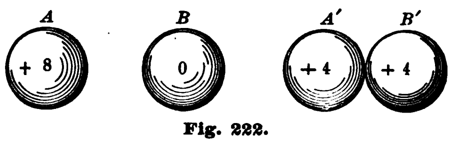

Fig. 222.

(Fig. 222) represent two brass balls, *A* charged with 8 units +, and *B* neutral. On contact (*A′B′*), the 8 units instantly spread over the surface of *B*, so that *A* and *B* each has 4 units of

positive charge. If A were $+8$ units, and B were $+10$ units, then, after contact, each would be $8+10\div 2$, or $+9$ units. If A were $+10$ units and B were -14 units, then each, after contact, would have a negative charge of 2 units, since $+10-14\div 2=-2$.

f. But if the spheres are not of equal size, their final shares will not be equal, for the larger one needs more electricity to charge it to as high degree as the smaller one, just as a wider jar needs more water than a narrow one to fill it to the same height. The spheres will divide the total charge on both in proportion to their radii. Thus if the radius of A (Fig. 223) is twice the radius of B, then after contact A will have twice as much of the total charge as B. The total charge is $15+3$, or $+18$, units. The radii being as $2:1$, the 18 is divided into $2+1$, or 3, parts; each is $+6$ units. A takes two of these parts, and B one.

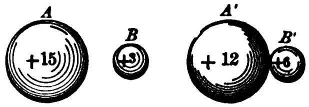

Fig. 223.

g. It is evident that B is as highly charged with its 6 units of electricity as is A with its 12 units, for there is no further loss nor gain by either when they touch each other, as there would be if one were more highly charged than the other. Conductors which take different quantities of electricity to charge them so that there will be no transfer from either to the other when they come into contact, are said to have different *capacities*. Thus the capacity of A (Fig. 223) is twice that of B, while the capacities of A and B (Fig. 222) are equal.

The electrical capacities of spheres are to each other as their radii, provided no other conductors are near. When other conductors are near, the capacity of an insulated conductor is increased by induction.

Experiment 125. — *Object.* To show that more electrification is required to charge an insulated conductor when another which is not insulated is near.

C and *C′* (Fig. 224) represent two sheets of tin foil smoothed out on the surfaces of clean, dry, glass plates, and fixed by gum at the corners. Each has a narrow tongue, *t*, folded over the edge of the plate.

Support *C* in vertical position with the foil turned away from the electroscope. It may be so placed by fixing the jaws of a wooden clamp upon the edge of the glass, without touching the tin foil. Join *t* to the knob of an electroscope by a slender wire. Support *C′* also, but at a distance from *C*. Now electrify *C* by drawing an electrified ebonite rod

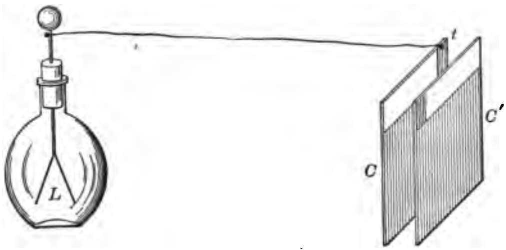

Fig. 224.

over *t*. The leaves will diverge much if *C* is highly charged, and little if it is not. Bring *C′* near and parallel to *C*, with the foil side toward *C*. Then watch the leaves while you touch *C′* with the moist finger. If the leaves partially collapse, it shows that *C* is less highly charged than before. Yet the quantity of electrification in *C* is the same as before. Impart more to *C* by touching *t* with electrified ebonite. The leaves may be made to diverge as much as at first, and then *C* is charged again as highly as at first. Touch *C′* a second time, and if the leaves collapse at all, add more electrification from the ebonite.

Thus it is shown that *C* takes more electrification to charge it to a certain degree when *C′* is near than when it stands alone. *Its capacity is increased by the presence of the insulated conductor.*

h. The increase in the capacity of an insulated conductor when near to, but not in conducting communication with, an uninsulated conductor, is due to induction (§ 177, *a*).

Thus in the foregoing experiment, the − charge on *C* electrifies *C′* through the air. Positive electrification is drawn to the surface nearest *C*, while the − is repelled to earth when *C′* is touched with the finger, thus leaving *C′* with a + charge. This + charge attracts the − of *C*, and holds it bound on the surface

which is nearest C', leaving the other surface with less. Hence, more can be added without charging C any more highly than before. *The mutual attraction of the unlike kinds on C and C' holds them bound upon the two surfaces nearest together*, while the non-conducting air keeps them separate. The two opposite electrifications are thus accumulated or *condensed* in much larger quantities than could be put upon either conductor if the other were not present.

180. **Condensers.** — *a.* A condenser is an instrument for accumulating large quantities of electrification on small surfaces by induction. Any two conductors, one of which is insulated, if separated by a non-conductor, form a condenser. Thus (Fig. 224), C and C', with the air between them, constitute a condenser. Two squares of tin foil with a plate of glass between them, and a goblet containing water with the hand around it, are simple forms of condenser.

b. The *Leyden jar* (Fig. 225) is a common and convenient form of condenser. It consists of a glass jar, coated, both inside and outside, with tin foil to within a few inches of the top, with a dry, hard-wood cover, through which passes a brass rod surmounted by a brass ball, with a chain reaching from its lower end to the bottom.

Fig. 225.

c. To *charge the jar*, place the knob in contact with, or very near to, a charged body, such as the conductor of an electrical machine, while the outside is held in the hand, or is otherwise put into conducting communication with earth. Electrification will pass directly from the charged body to the inside coating of the jar. There by induction the outside coating is electrified, the opposite kind being drawn to the surface of the glass while the same kind is repelled to earth.

To *discharge the jar*, make a conducting communication

between the knob and the outside. The two electrifications instantly and almost completely neutralize each other. Some form of a *discharger* should be used which will protect the hand from the shock which the passage of a large quantity of electrification produces. A good discharger (*AB*, Fig. 226) can be easily made. A piece of stout wire is chosen. A loop, *C*, which answers in place of the ball, is made at each end. The wire is bent sharply at the middle, and thrust through a hole in the stopper of a test tube. The branches are then separated as shown. Holding the discharger by the glass handle, place one loop against the outside of the charged jar, and bring the other near to the knob. The opposite charges in the jar instantly unite and neutralize each other. In other words, the jar is discharged.

Fig. 226.

d. The *charge resides in the glass,* and not in the coatings. This was proved by Benjamin Franklin, who used a jar with movable coatings (Fig. 227). The jar was first charged in the usual way, then placed upon an insulator. The inner coating was then lifted out by means of a holder made of insulating material, and, finally, the glass jar, *l*, was removed from the outside coating, *c'*. An electroscope was affected very little by either coating, but violently by the glass jar; and on putting the parts together again and using a discharger, a spark was obtained almost as brilliant as if they had not been separated.

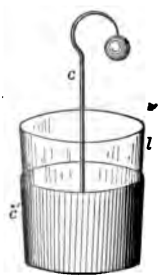

Fig. 227.

The charge of a condenser resides in the dielectric between the

conductors. The conductors simply distribute the electrification so that a larger extent of the dielectric is affected.

e. The *condition of the dielectric* is one of strain (§ 22, *a*, *c*), produced by the stress of the opposite electrifications, very much as a cord is strained when its two ends are pulled in opposite directions. And as there is a limit to the strain which the cord will bear without breaking, so there is a limit to the charge which a condenser will bear. When the strain becomes too great, a discharge takes place through the air over the top of the jar, or, if the glass is thin enough, through the glass itself. Whenever the air breaks, a spark is the result; if the glass cannot bear the strain, the jar is punctured and ruined.

f. The *capacity* of a condenser is the quantity of electrification which it may accumulate.

1. It is proportional to the area of its metallic conductors.

2. It is inversely proportional to the thickness of its dielectric.

3. It depends on the nature of its dielectric, because one substance transmits induction better than another.

A Leyden "battery" consists of two or more jars, with their inside coatings joined, usually by a wire which passes around their projecting rods, while their outside coatings are also connected, usually by standing on a sheet of tin foil. They are practically one jar, with coatings of larger area, but no greater thickness of glass. Hence larger charges may be accumulated.

181. **Electric Potential.** — *a.* One conductor is said to be "more highly charged" than another when it has more electrification in proportion to its capacity (§ 179, *g*). Thus sphere *A* (Fig. 228) having a radius, *R*, three times that of *B*, has three times the electric capacity, but, as shown, it is charged with more than three times the quantity of electrification. It is therefore more highly charged than *B*. When they are

brought into contact (Fig. 229), electrification passes from *A* to *B* until they are charged to the same degree, when *A*,

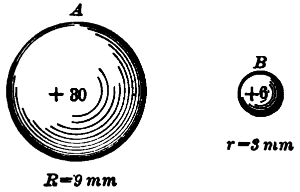

Fig. 228.

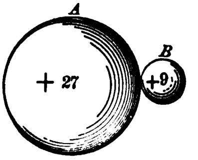

Fig. 229.

with three times the capacity of *B*, has also three times the electrification.

b. The transfer of electrification from a body more highly electrified to another which touches it may be compared to the flow of water from a vessel more highly filled to another, when a channel is opened between them. Thus a large quantity of water will fill the narrow jar (Fig. 230) to a higher level, *C*, than the same quantity will fill the broad one. But if a tube connecting the jars near their bottoms is opened, the water will flow from the one which is more highly filled into the other, until both are filled to the same level, *L*. In like manner (Fig. 229):

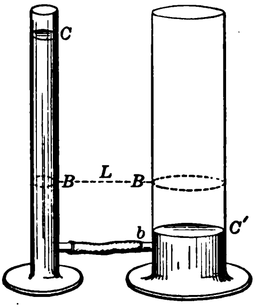

Fig. 230.

If one conductor is charged with more electrification in proportion to its capacity than another, electricity will flow from it to the other if there be a conducting pathway between them.

Example. — If the radius of sphere *A* is 8 cm., and that of sphere *B* is 28 cm., and if *A* is positively charged with 120 units, and *B* positively charged with 60 units, which is the more highly charged? Which will lose and which gain if they touch each other, and how much?

c. But the electrification of a charged body is a kind of potential energy (§ 17, *e*). And just as a given quantity of

water, standing at a higher level because it is in a narrower jar, has more potential energy, so a given quantity of electricity, in a body of lesser capacity, has more potential energy. Now a place where a given quantity of water has greater potential energy is said to be at a higher *level,* and a place where a given quantity of electricity has more electrical potential energy is said to be at a higher *potential.* Thus in a general way:

Electrical potential signifies the relative conditions of bodies or places which determine the direction in which electricity shall be transferred from one to another.[1]

d. In this sense potential is not an absolute, but a relative, quantity. It is described as "higher or lower." Places from which electricity is transferred are at higher potentials than places to which it goes. If there is no transfer between places that are in conducting communication, they are at the same potential.

For convenience the *potential of the earth* is considered to be *zero,* and all positively electrified bodies are said to be at potentials higher, while all negatively electrified bodies are said to be at potentials lower, than zero. So enormous is the capacity of the earth that no small addition or subtraction of electricity will change its potential perceptibly, so that all bodies in conducting communication with earth are at zero potential.

182. **Potential, Capacity, and Quantity.** — *a.* We have seen that the potential of a charge depends on the *quantity* of the electrification and the *capacity* of the conductor. With equal quantities the potential varies inversely as the capacity. With equal capacities the potential varies directly as the quantities. These laws apply only when the conductors have the same

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[1] The precise definition of potential may be found in more advanced works on electricity. See Thompson's *Electricity and Magnetism;* Barker's *Physics;* Daniell's *Principles of Physics.*

shape. When each of these quantities is measured, it is found that if we let V stand for potential, Q for quantity, and C for capacity, we have[1]

$$V=\frac{Q}{C}.$$

b. The *Electrostatic C. G. S. units* of these quantities are the following:

The unit of quantity, — that which will repel an equal quantity of the same kind with a force of 1 dyne when the two are 1 cm. apart in air.

The unit of capacity, — that of a sphere, whose radius is 1 cm., so distant from other bodies as not to be influenced by them.

The unit of potential, — the potential of a conductor whose capacity is 1 unit, when it is charged with a unit quantity.

Experiment 126. — *Object.* To verify the statement that electricity will go from a place of higher to one of lower potential, if the two are connected by a conductor.

C and C' (Fig. 231) are two gold-leaf electroscopes, with leaves and knobs as nearly of the same size and shape as possible. W is a copper wire

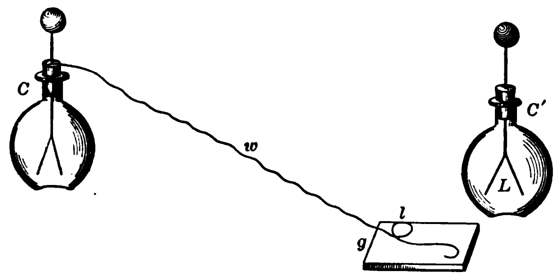

Fig. 231.

with one end bent around the rod of C, and the other, insulated by glass, g, ready to be hooked around the rod of C'. Use ebonite or glass to elec-

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[1] Also $C=\frac{Q}{V}$. But since $\frac{Q}{V}$ is the ratio of the quantity of electrification to the potential of the body charged by it, we may define capacity as a numerical value: *Capacity* is the *ratio* of the *quantity of electrification on a body* to its *potential.*

trify C very slightly, causing a little divergence of the leaves. Electrify C' more highly, causing a large divergence of the leaves. Now consider: The electroscopes, being of the same size and shape, have *equal capacities* (§ 179, *g*). Hence, since the leaves of C' diverge more, there must be a *larger quantity* of electrification in C' than in C. C', having more than C in proportion to its capacity, must be at a *higher potential* than C.

Hook the free end of w upon the rod of C', lifting it by means of a dry glass rod inserted into the loop, l. If the leaves in C' diverge less, and those in C more, than before, then electricity was transferred from C' to C, that is, from the higher to the lower potential.

Experiment 127. — *Object.* To ascertain whether all parts of the surface of a charged conductor are at the same potential.

C (Fig. 232) represents an elongated insulated conductor; C', a gold-leaf electroscope; P, a proof plane; w, a fine copper wire, No. 30, four to six feet long.

Attach one end of w to the knob of the electroscope, and the other to the disk of the proof plane. Electrify C by contact with electrified ebon-

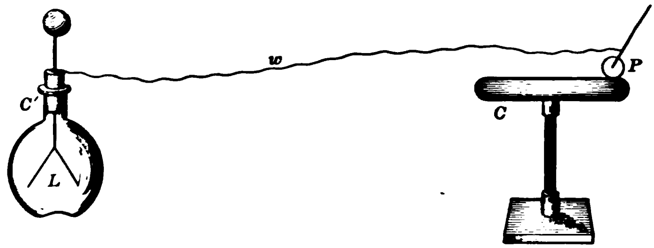

Fig. 232.

ite. Place the disk of P on the surface of C, and notice the divergence of the leaves, L. Move P to many different points on C, and notice whether the leaves diverge more or less. They will diverge more if P touches a place of higher potential. If the divergence of the leaves remains constant, then *the* potential *of the conductor is the same at all points on its surface, notwithstanding the difference in* density (§ 179, *d*).

Experiment 128. — *Object.* To compare the potential at different points on a conductor which is electrified by induction.

With the electroscope, wire, and proof plane arranged as in the preceding experiment, proceed as follows: Fix the rod of ebonite firmly in a clamp, and place it near that end of the insulated conductor, C, which is farthest from the electroscope. Electrify the ebonite by friction with fur. Let no electricity pass directly from the ebonite to the conduc-

tor. If everything is right, C is electrified positively at one end and negatively at the other (§ 177, *b*). Now test the potential by applying the proof plane to different parts of the surface of C, and notice the divergence of the leaves. If the divergence remains constant, then *the* **potential** *of the conductor is the same at all points on its surface, notwithstanding the differences in both* **density** *and* **kind** *of electrification.*

Experiment 129. — *Object.* To compare the potential of the inside surface of a hollow conductor with that of the outside.

Insulate a cylindrical metallic vessel by placing it on an inverted, dry, glass tumbler, and arrange the electroscope and proof plane as in preceding experiments. Electrify the vessel by touching it with electrified ebonite. Touch the inside surface with the proof plane, and observe the divergence of the leaves. Pass the proof plane over the edge to the outside surface, and notice the change, if any occurs, in the leaves. If the divergence of the leaves is not changed, then *the* **potential** *of the inside surface of a hollow conductor is the same as that of the outside surface, notwithstanding the fact* (§ 179, *b*) *that the* **charge** *is upon the outside only.*

c. The following facts are revealed by the foregoing experiments:

1. The flow of electrification from one place to another is not caused by a difference in the electric density at those places.

2. The flow of electrification from one place to another is not caused by a difference in the kind of electrification at those places.

These are *facts*, confirmed by all experience. The student may find them discussed in more advanced works on electricity. But it may be remembered that *potential* is to electrification, what *pressure*, due to gravity, is to fluids, and this conception will be very useful.

ELECTRIC CURRENTS.

183. **The Current.** — *a.* Electrification, while passing from a place of higher to a place of lower potential, along a conductor, is called an *electric current.*

In the discharge of a Leyden jar, for example, there is a momentary current through the discharger; and if a hand is

laid upon an electrified body, there is a momentary current through the person. Whenever two bodies, charged to different potentials, are joined together by a wire, there is a *sudden and complete* change to equal potentials by a *momentary current* through the wire.

b. A *continuous current may be kept up* by supplying the electrification to the two bodies as fast as it is transferred, — that is to say, *by keeping up their difference of potential.*

A difference of potential can be maintained in many ways, but in every case there must be a device which will take some other form of energy, and convert it into electrification.

A *voltaic battery* maintains a difference of potential by the expenditure of *chemical energy.*

A *dynamo* maintains a difference of potential by the expenditure of *mechanical energy.*

A *thermo battery* maintains a difference of potential by the expenditure of *heat energy.*

c. The properties of an electric *current* are very different from those of an electric *charge.* While an electric charge makes itself known by *exerting force,* — attraction or repulsion, — an electric current makes itself known by *doing work.* It may deflect a magnet, decompose a chemical compound, heat a wire, or drive a motor.

All continuous currents are alike in many respects. The student should first become fully acquainted with these common characteristics, and with the language used to describe them. The most convenient typical current, for these purposes, is that which is maintained by chemical action in what is called a *voltaic cell.*

184. **A Simple Voltaic Cell.** — *a.* The cell is represented by CC' (Fig. 233). It consists of two plates of metal, one, amalgamated zinc (z), the other, copper (c), partly immersed in dilute sulphuric acid. At the top of each plate is a binding screw by which to fasten wires (w, w').

b. So long as the plates do not touch each other, and the wires are kept separate, no action is visible. But if the wires are brought together, so that *there is a conducting pathway between the plates,* then first, bubbles of gas will appear upon the surface of the copper plate, and if the experiment is prolonged, the zinc plate will be found partially dissolved away. And second, if the wires are so long that one of them may be placed parallel to, and just above, a magnetic needle (L), the needle will be quickly turned aside.

The first of these facts shows that chemical changes are taking place in the cell, and the second shows that energy has been imparted to the wire outside.

Fig. 233.

c. The plates, the liquid in the cell, and the outside conductor, taken together, constitute the *circuit.* When this conducting pathway is complete, the circuit is said to be *closed.* But if there is a nonconductor at any point in it, the circuit is said to be *open* or *broken.* There is no energy in the wire, nor should there be any chemical action visible in the cell, when the circuit is open.

The following investigation will reveal the important details of the actions in the voltaic circuit.

Experiment 130. — I. *To study the action of dilute acid on zinc and copper separately.*

1. Put about 100 cc. of water into a bottle or beaker which would hold about twice as much, and add 5 or 6 cc. of strong sulphuric acid. Drop

several pieces of *clean*[1] sheet zinc into this dilute acid. The action should be brisk. Bring a lighted match to the mouth of the bottle. Describe the actions in detail.

2. Insert a strip of copper into a fresh portion of dilute acid. Note the result.

3. Fill an ordinary tumbler about two thirds full of dilute acid. Insert a strip of clean zinc, and beside it, but not touching it, a similar strip of copper. Note the result.

4. Remove the zinc, and *amalgamate* it by laying it flat upon a plate in contact with just a little mercury, and spread the mercury over both sides of it by gently rubbing it with a cloth. It should become silvery bright at all points. Place the amalgamated zinc in the acid. Note the result.

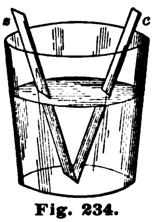

Fig. 234.

II. *To study the action of dilute acid on zinc and copper when the metals touch each other.*

1. Fig. 234 represents strips of zinc and copper, in contact at their lower ends, in dilute acid. Try unamalgamated zinc first. *Note fully.* Then try amalgamated zinc. *Note fully.*

2. Let the metals touch each other at their upper ends only. *Note fully.*

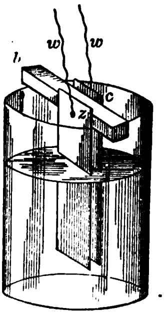

Fig. 235.

III. *To study the action of dilute acid on amalgamated zinc and copper when their upper ends are connected by a wire.*

Use the more permanent arrangement of the simple cell (Fig. 235), in which the metal strips, *z* and *c*, are each fastened by a screw to a bar of dry wood. The wood insulates the metals from each other and supports them in the jar of acid.

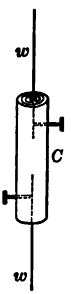

Fig. 236.

1. There should be little or no action. But bring the ends of the wires together, and decide whether the wire connection has the same effect as making the metals touch each other.

2. Ascertain whether the connecting wire may be lengthened without impairing the effect perceptibly. The ends of a long wire may be joined to *w*, *w* by *connectors* (*C*, Fig. 236).

IV. *To detect the energy of the connecting wire.*

In addition to the long connecting wire a "magnetic needle" (*L*, Fig. 237) is required. A large sewing needle may be magnetized by

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[1] New, bright zinc should be scoured with sandpaper.

drawing it repeatedly across the pole of a magnet (Experiment 14). It may be suspended in a horizontal position by a fine silk fiber. Then proceed as suggested by Fig. 237, the principal thing being to place one part of the long connecting wire parallel, near to, and either above or below the needle (*NS*), while the return branch is on the opposite side of it or at a much greater distance on the same side. Note the evidence of energy in the air near the connecting wire. Open the circuit *a*; note evidence of the loss of energy.

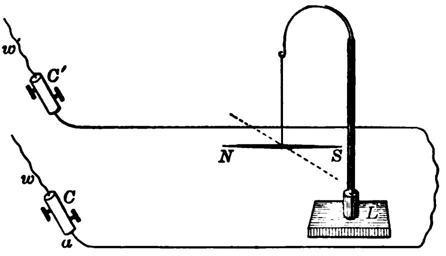

Fig. 237.

V. *To find out whether the acid acts on the zinc, or the copper, or both.* Weigh the two plates (III.), which should be clean and dry, separately. Place them in the acid with their lower ends together (II.), and leave them a few hours, perhaps overnight. Then dry and weigh them again. Remember that loss of weight signifies chemical action.

Where does the action in the cell appear to the eye to be? Where does it prove by this experiment to be?

These experiments have shown:

1. That dilute sulphuric acid acts chemically upon common zinc, but not on amalgamated zinc, or copper separately. Give the evidence.

2. That there is chemical action if the amalgamated zinc and copper are in conducting communication, either in or outside the liquid. Give the evidence.

3. That there is energy in the air around the conductor when the circuit is closed, which does not exist when the circuit is open. Give the evidence.

4. That while the bubbles of gas escape from the surface of the copper, the chemical action is due to the zinc and not to the copper.

185. **The Chemical Actions in the Cell.** — *a.* The chemical action in the cell is between the zinc and acid. There is no change in the copper. The molecules (§ 31, *e, f*) of sulphuric acid consist of atoms of hydrogen (H); of oxygen (O), and of sulphur (S). Now what happens is this. Atoms of zinc *take the place of* atoms of hydrogen, and produce molecules of a

new substance called *zinc sulphate*, which remains in solution while the hydrogen escapes in bubbles.

$$H_2SO_4 + Zn = ZnSO_4 + H_2.$$

Sulphuric acid and *zinc* produce *zinc sulphate* and *hydrogen.*

b. This action must occur at the surface of the zinc, but the hydrogen appears at the surface of the copper instead. It is transferred through the liquid in an invisible form.

This curious fact is accounted for by supposing that all the molecules of acid between the plates are affected, but not completely shattered, and that throughout the line there is a constant exchange of atoms going on among them. By this exchange the hydrogen atoms are handed along from one to another molecule, always toward the copper, while the SO_4 is handed along toward the zinc plate.

Thus suppose a line of acid molecules, $\frac{H_2}{SO_4}$, between the zinc and copper plates when the circuit is open, as represented in the diagram (*O*, Fig. 238). When the circuit is closed, as shown at *C*, the molecule next the zinc is broken; its SO_4 combines with the zinc, and the new molecule, $ZnSO_4$, sinks away, while the SO_4 of all the other molecules slide over toward the zinc plate, and the H_2 slides over toward the copper plate. Each H_2, except the last, meets an SO_4, by which it is kept from going off as free gas. But the last H_2, meeting no SO_4, escapes. Thus free hydrogen gas escapes at the copper plate, and free zinc sulphate at the zinc plate, while sulphuric acid is being re-formed all along the line.

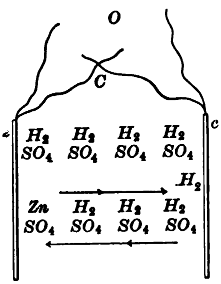

Fig. 238.

186. **The Electrical Conditions in the Cell.**—*a.* According to the chemical theory of the cell, the difference of potential, to which the current is chiefly due, exists between the metals

and the liquid of the cell. Both zinc and copper are at higher potentials than the liquid, but *the zinc is about one unit higher than the copper.* When the circuit is open there is a *stress* in the liquid field between the metals, directed toward the copper. But when the circuit is closed, two things happen: There is a *transfer* of electrification through the liquid to the copper, and thence along the conductor outside, back to the zinc plate, and there are the *chemical changes* of the zinc and acid. The SO_4 is supposed to be charged with positive electricity when it leaves the H_2, and to impart it to the zinc plate when it is converted into zinc sulphate. In this way the potential of the zinc plate is continually kept up, and, consequently, a continuous current must exist through the liquid, the copper, the outside conductor, and the zinc plate, back to its starting point in the liquid.

b. The *difference* of potential and the consequent *direction* of the current are shown in Fig. 239.

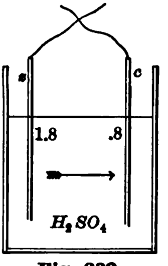

Fig. 239.

The potential of zinc in acid is about 1.8 units (volts) higher than that of the acid.[1]

The potential of copper in acid is about .8 units (volts) higher than that of the acid.

Hence the potential of zinc in acid is about 1 unit higher than that of copper in acid.

As the transfer of electrification takes place from higher to lower potentials, the *direction* of the current must be *from zinc through liquid* TO *copper,* and thence *through the outside conductor* FROM *copper to zinc.*

c. The binding screws, or the ends of the wires attached to the plates, are called the *poles* or the *terminals* of the cell.

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[1] Thompson's *Elementary Lessons in Electricity and Magnetism,* p. 152. These figures are not exact. Different values are given by different authorities. But the exact numerical values are less important here than the explanation, which is illustrated by approximate figures.

The upper end of the copper plate has a higher potential than that of the zinc plate; hence *the copper pole is positive* and the zinc pole is negative.

187. **The Galvanoscope.** — *a.* Any instrument by which to detect the presence of a current and discover its direction, is a *galvanoscope.* It usually consists of a magnetic needle suspended in a coil of wire.

We have seen (§ 184, *b*) that a magnetic needle is turned aside by a current passing over it; some further study will show that the direction in which the needle turns depends on the direction of the current along the wire.

Experiment 131. — *Object.* To study the deflection of a magnetic needle by the energy of a current in its neighborhood.

1. A magnetic needle, suspended by a fiber (Fig. 237) or balanced on a pivot, settles to rest with one end pointing northward (N) and the other southward (S). Join the poles of a simple cell by a long copper wire. Hold a part of this wire *above* the needle and *parallel* to it, and so that the current on its way from copper to zinc will *go from N to S.* Observe that the *N-pointing* end of the needle turns toward the *east.* Prove that this is not accidental. Hold the wire above the needle as before, but so that the current will go from S to N. Record the *direction* in which the *N-pointing* end turns.

2. Place the wire *below* the needle, and record the direction in which the *N-pointing* end turns when the current goes from N to S, and then also when it goes from S to N.

3. Bend the wire around the needle so that the current will go from N to S *above* the needle and from S to N *below* it at the same time. Record the direction in which the N end turns, and also whether its deflection is greater or less than when the current went only one way.

b. These experiments should reveal two facts:

1. Whenever the N end of a magnetic needle turns eastward, the current which deflects it is going from N to S through the wire which lies above it.

2. Whenever the N end of a needle turns westward, the current which deflects it is going from S to N along the wire which lies above it.

The following rule is a more useful way to state the facts:

Place the hand on the wire, with the palm toward the needle, and the outstretched thumb pointing in the direction in which the north end of the needle swings; the outstretched fingers will then point the direction of the current in the wire.

c. The galvanoscope is made in many forms, and the same instrument is not equally well adapted to all currents. In Fig. 240 a coil of *many turns of fine wire* is shown upon a wooden base. Above it is a dial graduated to show how far the needle is deflected. The needle lies inside the coil, suspended by a silk fiber, while a light pointer fixed to the needle swings above the dial. In Fig. 241 a coil of *few turns of thick wire* is fixed upon the base. The coil, the needle, and the dial are inclosed in a box with a glass top. The first is a "high resistance," and the second a "low resistance," galvanoscope.

Fig. 240.

Fig. 241.

A simple but useful instrument can be easily made; it is represented by Fig. 242. *AA* represents a light wooden box, 12 cm. square inside and 12 cm. deep; *L*, a rectangular wooden frame, 3 cm. high, with a flat coil of insulated wire wound lengthwise, one or more layers, with its ends passing through the box to the binding posts, *CC′*;

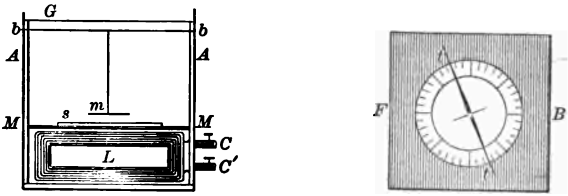

Fig. 242.

M, a square of looking-glass, and *s*, a graduated paper ring cemented on the glass. A brass wire, *bb*, is stretched across the box near the top,

and a silk fiber, from its middle point, supports a needle, 1.5 cm. long, 2 or 3 mm. above the center of the scale. *FB* shows the mirror, scale, and needle as seen from above. A long glass-thread pointer, *tt*, made by drawing out a piece of tubing (Experiment 26), is fixed at right angles to the needle. A glass cover, *G*, protects the whole.

d. The *astatic galvanoscope* (Fig. 243) is a more sensitive form. Its construction differs essentially in the needle. Two nearly equal needles are fastened together by a crossbar, with the N end of one opposite the S end of the other. The combination is suspended by a silk fiber, with the lower needle inside the coil *CC'*, as shown (Fig. 243). The earth's force is nearly neutralized in this way, because the attraction for N is nearly equal to the repulsion for S, and so the force of the current swings the needle with less opposition.

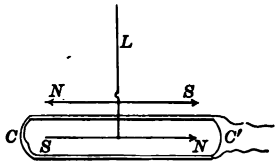

Fig. 243.

e. Galvanoscopes do not *measure* a current (§ 187, *a*). Instruments for measuring currents are called *galvanometers.* These are galvanoscopes so constructed that the deflections of the needle bear some numerical relation to the strength of the currents which produce them. A *tangent galvanometer* is shown by Fig. 244. In this instrument a very short needle is pivoted *at the center* of a circular coil, *whose diameter is twenty or thirty times the length of the needle.* In this case *the strengths of two currents are proportional to the tangents of the deflections which they produce.*


Fig. 244.

The simple instrument described in *e* may be used as a tangent galvanometer for deflections up to 40°, and with no serious error in ordinary work up to 50°.

f. Very sensitive instruments will not stand strong currents without injury. They should always be protected by letting only a very small current go through them. How the current can be reduced for this purpose is illustrated by Fig. 245. A current from C' on reaching L has the choice of two paths, one through the galvanometer, G, the other through the wire, LC; it divides between them, and the shorter and larger the wire LC, the larger will be the portion of current which it carries, and the less will be the current through the galvanometer (§ 194, *c*, 1, 2). By varying the size and length of this wire, the current through the galvanometer may be reduced as much as need be. Such a wire is called a *shunt*. A shunt is a branch wire which carries a part of the current outside of the instrument.

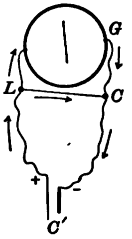

Fig. 245.

g. It is often desirable to reverse the direction in which a current is passing through an instrument. This is most easily done by means of a *commutator*.

A simple and good form is shown by Fig. 246.[1] W represents a block of wood with three holes 1 cm. deep, one of which is shown at m. They are in a straight line, 3 cm. apart, and contain mercury. L is a piece of hard wood, pierced by two wires, 3 cm. apart, which are fixed to binding posts, a and b, and extend into the mercury cups below. Binding posts, C, C', B, communicate with the mercury cups. The − pole of the battery is joined to both C and C', and the + pole to B. A galvanometer G, is shown, joined to a and b. To *close circuit*, place L over the first and second mercury cups. To *open* circuit, lift L. To *reverse the direction* of the current through G, carry L over to the second and third mercury cups. The student should trace the paths of the current in each case.

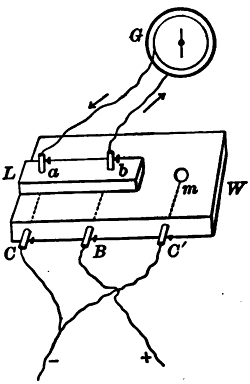

Fig. 246.

[1] The "mercury commutator," as modified by the author.

188. Voltaic Cells with Different Materials. — *a.* Zinc, copper, and sulphuric acid are not the only substances which will produce a current. Iron may take the place of zinc, platinum or carbon may take the place of copper, and other liquids may be used instead of sulphuric acid. The following condition, however, is practically vital: *There must be two solid conductors, and a liquid which will act chemically upon one more vigorously than upon the other.*

But each combination of materials differs from every other, in its power to produce a current. The two essential points of difference are, first, the *difference of potential* which the cell can maintain, and, second, the *direction of the current* which it produces.

Experiment 132. — *Object.* To compare the currents produced by cells consisting of different materials.

Set up the apparatus as shown in Fig. 247. *L* is a wooden bar; *w*, *w'* are two wires to connect the plates of the cell with the galvanoscope, *G*. These wires pass through small holes in *L*, which they fit *tightly*, in order to support the weight of the plates below without slipping. The plates are provided with wires, and are joined to *w*, *w'* by the connectors *C*, *C'*. *L* may be held by the jaws of a clamp at such height that the plates may be properly immersed in the liquid of the cell.

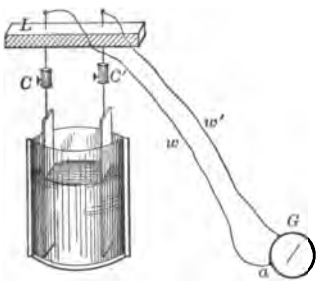

Fig. 247.

Zinc, copper, carbon, iron, lead, and tin, with dilute sulphuric acid, and a solution of chromic acid, may be tested. Since we wish to discover differences due wholly to different *materials*, we should make our cells as nearly as possible *alike in all other respects*. Thus the plates should be of the same size, immersed to the same depth, and at the same distance apart, and the same connecting wires should be used throughout the investigation. The arrangement of apparatus (Fig. 247) fulfills these conditions.

Adjust the galvanoscope so that the needle, when at rest, shall lie over the NS or 0 line of the scale, and parallel to the wire in the coil. Suspend a zinc and a copper plate from the connectors; insert them in

dilute sulphuric acid, and join one of the leading wires to the galvanoscope. Join the other leading wire to the galvanoscope, and record the direction in which the N end of the needle swings, and also the angle at which the current holds it. Open the circuit *at a* only, as soon as the angle has been read. Substitute another plate, say carbon, for the copper. Make as many different combinations as practicable. Tabulate the observations.

Experiment.	Combination.			Swing of N End.	Current in Wires.	Deflection.
	Plates.		Liquid.			
No. 1	Zinc	Copper	Sulp. Acid	East	C⟶Z	40°
——	——	——	——	——	——	——

Which is the + pole of each combination?
Which combination appears to give the strongest current?

b. While a galvanoscope will not *measure* a difference of potential, it will show whether one cell maintains a greater difference than another, because a greater difference of potential causes a stronger current, and a stronger current swings the needle farther. Therefore the deflections of the needle in the foregoing experiment should enable you to decide, (1) which combination maintains the greatest difference of potential, and (2) in what order the others follow.

189. **Polarization and Constant Cells.** — *a.* A serious obstacle in the way of maintaining a steady current is found in the polarization of the cell. *Polarization* consists in the accumulation of hydrogen upon the surface of the copper plate (§ 185, *b*). The hydrogen film weakens the current in two ways: *It makes the difference of potential in the cell less,* because the gas is in a positive condition more nearly equal to that of the zinc; and *it increases the resistance which the current must overcome* in the cell, because it is a poor conductor. Hence the current from a simple cell will gradually become weaker and weaker.

b. How can polarization be prevented? In general, by any

means which will prevent the deposit of the gas upon the copper. Keeping the plates in motion or agitating the liquid will do this, but not in the most practical way. The better plan, generally adopted, consists in using up the hydrogen by chemical action. A special substance is provided in the cell by which the hydrogen is converted into water. The substance by which polarization is prevented is called a *depolarizer*. A cell in which polarization is prevented, so that its current does not vary in strength, is called a *constant cell.*

c. The forms of cells are so numerous that volumes have been written to describe them.[1] The *essentials* of every practical form are, however, the same: Two solids with an exciting liquid which acts chemically on one more vigorously than on the other. They differ in the *materials* chosen for the three essential parts, and in the *devices used to prevent polarization.* The choice of materials determines the difference of potential in the cell, while different depolarizers determine the constancy of the current.

190. **Electrolysis.** — *a.* We have seen that a voltaic cell yields a current by transforming chemical energy into electrical energy. We are now to see how the energy of a current may be transformed back again into chemical energy.

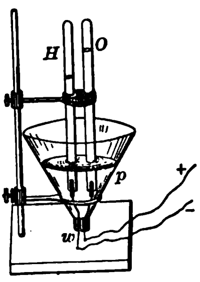

Fig. 248.

Experiment 133. — We are to pass an electric current through dilute sulphuric acid and collect the products.

The neck of a funnel having been cut short, as shown in Fig. 248, is closed with a stopper through which pass two platinum wires, *w*, each terminating in a strip of platinum foil, *p*. Very dilute sulphuric acid, consisting of 1 part acid to 20 parts of water, covers the platinum strips. Over the platinums invert glass tubes previously filled with the dilute acid. The funnel and tubes may be supported by means of a retort stand. Connect the wires, *w*, with a battery of two

[1] Carhart's *Primary Batteries;* Benjamin's *The Voltaic Cell.*

or more cells in series. Bubbles of gas escape from the platinums, and nearly twice as fast from the negative strip as from the other. These gases are oxygen (O) and hydrogen (H) as may be shown by testing them with a match flame.

In this experiment the energy of the current has been expended to separate the atoms of hydrogen and oxygen which were bound together in the molecules of the acid, and it now resides in the two gases as potential chemical energy.

b. The decomposition of a liquid by a current is called *electrolysis;* the liquid decomposed is called the *electrolyte.* The + terminal or electrode in the liquid is called the *anode,* and the − electrode is called the *cathode.* Because the oxygen is set free from the anode it is called an *electro-negative substance,* while the hydrogen which is set free from the cathode is called an *electro-positive substance.* As a further illustration make the following experiment:

Experiment 134. — Use solution of copper sulphate as the electrolyte in place of dilute sulphuric acid (Fig. 248). Oxygen will be collected, as before, over the *anode;* but instead of hydrogen being set free at the *cathode,* metallic copper will be deposited thereon. The electro-negative substance liberated from copper sulphate proves to be oxygen; and the electro-positive, copper.

c. Other metals may be deposited by electrolysis. Thus if a current is passed through a solution of silver cyanide, the cathode will be coated with silver, or "silvered;" if through gold cyanide, the cathode will be coated with gold, or gilded.

The process of covering the surface of an article with a somewhat durable coating of metal, by an electric current, is called *electroplating.* Sometimes the metallic deposit is intended to be removed, and used independently of the object on which it was deposited; in this case the process is called *electrotyping.* Copies of medals and the plates from which books are printed are common forms of electrotypes consisting of copper.

191. **Secondary Batteries.** — *a.* As the energy of a current may be converted into potential chemical energy by electroly-

sis, so this potential chemical energy may be reconverted into the energy of a current. Secondary batteries are for this purpose. A *secondary cell* is one in which the chemical energy of the ions — the substances set free by electrolysis — is converted back again into electric current.

b. The cell consists of two plates of lead, both covered with a paste of red oxide of lead and sulphuric acid, or one with the red oxide and the other with litharge, immersed in dilute sulphuric acid. Such a cell will yield no current until it is *charged*. To charge it, an electric current is sent through it. By electrolysis of the liquid, oxygen is liberated at the + plate and hydrogen at the − plate. The oxygen combines with one of the lead oxides; the hydrogen takes oxygen from the other; and the energy of the current now exists as chemical energy in the two coatings. This energy may remain, thus stored in the cell, for many days. On this account the cell is often called a *storage cell*. But if the poles of this charged cell are connected, the chemical action is reversed, and an electric current is the result.

192. **Representing and Grouping Cells.** — *a*. When a more powerful current than one cell can yield is wanted, two or more cells are joined together, and the group of connected cells is called a *battery*.

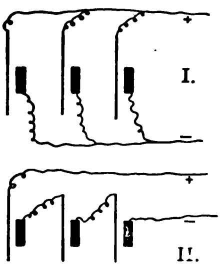

Fig. 249.

b. Cells may be joined in two ways. Thus suppose we have three zinc-copper cells; then,

1. We may connect all the zinc or − poles together, and all the copper or + poles together, as shown in Fig. 249, I., where cells are represented by a conventional symbol, — a long thin line for the lower potential plate, and a short thick line for the higher potential plate. This method is called joining *in parallel*, or *in multiple arc*.

2. We may connect the poles alternately, the + pole of one cell with the − pole of the next, as in Fig. 249, II. This method is called joining cells *in series.*

193. **Electromotive Force.** — *a.* We have seen (§ 186, *b*) that the electric action in a cell is directed from the zinc through the liquid to the copper, and thence outside from the copper to the zinc. Now this directed action is what is called the *current.* The cause of the current is called *electromotive force,* as the cause of a current of water is called *gravity.* It is often called *electrical pressure,* on account of its fancied resemblance to the pressure which urges water from higher to lower levels.

b. The E.M.F.[1] of a current, in the connecting wire outside a cell, is *proportional to the difference of potential between the poles,* just as the pressure of water in a jar is proportional to the difference of level between its top and bottom.

c. The electromotive force of a cell *depends on the materials used* (Experiment 132). It has a certain value, always the same, when the cell consists of zinc, copper, and dilute sulphuric acid of definite strength and at the same temperature; but it has a different value in a cell containing iron in place of zinc, or platinum in place of copper, or chromic acid in place of sulphuric acid. Each combination of materials maintains its own specific electromotive force, without regard to the size of the plates or the extent of the liquid between them.

d. When two or more cells are joined *in parallel,* the E.M.F. is not increased, because all the + plates being joined together are one continuous conductor, and hence must have the same potential; and all the − plates for the same reason must have the same potential. The difference in potential is not changed, and hence the E.M.F. should be the same as that of a single cell.

But if cells are joined *in series,* the E.M.F. is increased.

[1] An abbreviation for *electromotive force.* It should be read always in full — "an electromotive force," and not "an E.M.F."

The + plate in one is connected with the − plate in another; hence the difference of potential of one cell must be added to that of the next. The final difference, and therefore the E.M.F. (§ 193, *b*), should be the sum of them all.

e. The *practical unit* of E.M.F., or electrical pressure, is called the *volt.* The volt is very nearly the E.M.F. of a single zinc-copper-dilute-acid cell.

Since E.M.F. is that which urges the current along, an increase in its strength should increase the current.

194. **Resistance.** — *a.* We have seen (§ 175, *a*, *b*) that substances differ in their power to conduct electrification. All substances obstruct the passage of the current more or less. That property of matter by virtue of which it obstructs the passage of a current, is called *resistance.* If the poles of a cell are connected by a glass rod, no current is obtained because the resistance of glass is very high; but if they are connected by a copper wire, a current flows freely, because the resistance of copper is low. Since resistance always opposes the flow of electricity, an increase in it must diminish the current. Good conductors offer small resistance and permit more current to flow. *Conductivity* and *resistance* are the reciprocals of each other.

Experiment 135. — *Object.* To discover whether the strength of a current depends on the material of the conductors which connect the poles of the cell.

Make three trials, *alike in all respects* except that different kinds of wire are used to complete the circuit. Use the same cell and immerse the plates to the same depth, for all the trials.

1. Support the plates of a zinc-copper cell out of the liquid[1] (Fig. 250), while you make connections as follows: Join one pole to the galvanoscope, *G*, by a short wire, *s*, and the other pole to the galvanoscope by about 10 feet of No. 30 copper wire, *ww*, which may be kept from kinking

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[1] "Bichromate Solution" is better than dilute acid because the polarization of the cell is less. To make it: Dissolve 115 g. of sodium bichromate in 1000 cc. of cold water. Add slowly, with constant stirring, 110 cc. of strong sulphuric acid. Let the hot solution cool before using it.

or touching itself by passing around a bottle, C'. See that the coil of the galvanoscope is parallel to the needle at rest. Immerse the plates, and note the deflection of the needle.

2. Lift the plates from the liquid while you put *an equal length* of No. 30 iron wire in place of the copper. Immerse the plates, and note the deflection.

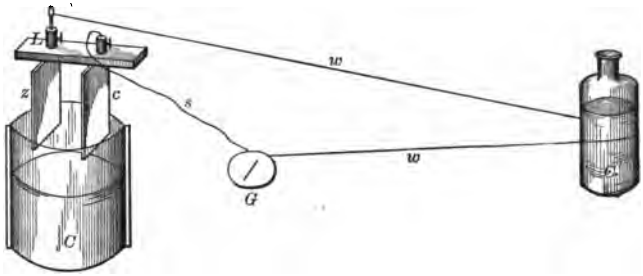

Fig. 250.

3. Repeat with an equal length of No. 30 German silver wire.

Remember that a larger deflection shows a stronger current. Which of the wires used transmits the strongest current? Which obstructs the current most? All other things being equal, which offers the greatest resistance, copper, iron, or German silver?

Experiment 136.—*Object.* To discover on what the resistance of a conductor of a given material depends.

Pass the current from the same cell through wires of the same material, but of different lengths and diameters. The wires may be attached to English binding posts set in a board (Fig. 251), so that the distance be-

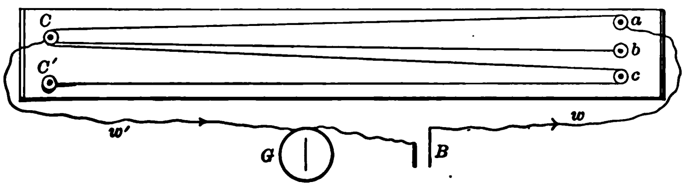

Fig. 251.

tween one, C, and each of the three others, a, b, c, shall be 1 m. A fifth post, C', may be placed 1 m. from c. The cell, B, the galvanoscope, G, and the wire to be tested are to be joined in series as shown. A German silver wire, No. 30, is to extend from a, around C, to b. Another German silver wire, No. 28, is to extend from C, around c, to C'.

Or the frame can be dispensed with, and the wires fixed as in Fig. 250. Thus longer wires may be used at pleasure, by passing them several times around two bottles (*E*, *F*, Fig. 260), a meter apart.

1. Fix one leading wire, *w*, to *a*, and the other, *w'*, to *C*, and read the deflection of the galvanoscope. Note, in a tabular form, the size of the wire *aC*, its length, and the deflection. Insert 2 m. by changing connection of *w'* from *C* to *b*. Insert ½ m. by pressing the end of *w'* on *aC* half way between the posts. These observations show that the resistance of a wire depends on the length of a conductor. What relation is revealed?

2. Pass the current through the 2 m. of No. 28 wire. Compare the deflection with that obtained when 2 m. of No. 30 wire was used. This experiment shows that resistance depends on the size of a conductor. What relation is revealed?

3. Join *a* and *b* by a short wire. Then fix one wire, *w*, to *a*, and the other, *w'*, to *C*. Now, on reaching *a*, the current is divided. One part goes over each of the two wires to *C*. Compare the deflection with that obtained with the 2 m., the 1 m., and the ½ m. in the first set of observations. The result should reveal the effect on resistance of joining two conductors *in parallel*.[1] What effect is shown?

4. Two meters of iron wire, No. 30, may be wound around bottles, tested, and compared with the 2 m. German silver wire, to discover whether resistance depends on the material of the conductor.

And again, 5 m. of iron wire and 30 m. of copper wire of the same size (No. 30) may be used, and the results compared.

b. The *practical unit of resistance* is called the *ohm*. The ohm, as precisely defined by electricians, is the resistance of a column of pure mercury at 0° C., 106.3 cm. long, containing 14.4521 g. The cross section of this column is about 1 sq. mm.[2] It is well to remember that 300 feet of common iron telegraph wire has a resistance of about 1 ohm. A ready laboratory standard for illustration is 9.3 feet of No. 30 (B. & S.) copper wire; its resistance is very nearly 1 ohm.

c. By carefully *measuring* the resistances of conductors (§ 198) the following laws have been revealed:

[1] Two conductors in parallel are equivalent to one of larger size having a cross section equal to the sum of the cross sections of the two.

[2] This is known as the international ohm because it has been fixed by congresses of electricians made up of delegates from several countries. It is a little larger than the older ohm, known as the British Association ohm, or B. A. ohm. 1 international ohm = 1.013+ B. A. ohms.

1. *The resistance of a conductor of uniform cross section and material is directly proportional to its length.* Thus if the resistance of 9.3 feet of copper wire, No. 30, is about 1 ohm, that of 100 feet of the same wire is about $\frac{100}{9.3}$, or 10.75, ohms. The resistance of 300 feet of iron telegraph wire is about 1 ohm; what is the resistance of 1 mile of the same wire?

2. *The resistance of a conductor of given length is inversely proportional to the area of its cross section.* In round conductors, such as wires, the areas of cross sections, and therefore the resistances, vary inversely as the squares of their diameters. Thus, other things being equal, a wire whose diameter is twice that of another offers but $\frac{1}{4}$ as much resistance. The diameter of No. 30 copper wire is .01 inches; if the resistance of 9.3 feet is 1 ohm, the resistance of the same length of No. 18, whose diameter is about .04 inches, is only $\frac{1}{16}$ of an ohm.

3. *The resistance of a conductor of given length and cross section depends on the material of which it is made.* Thus the resistance of 9.3 feet of copper, No. 30, is about 1 ohm, but it takes only 1.32+ feet of German silver wire, No. 30, to give the same resistance.

4. *The resistance of a conductor of a given length and cross section depends on its temperature.* A rise of temperature increases the resistance of all metals; it diminishes the resistance of carbon, and also of all nonmetallic liquid conductors. Thus the liquid in a cell offers less resistance when warm than when cold, while the leading wires outside offer more.

d. At a given temperature the resistance, R, of a conductor is fixed by the length, l, the cross section, a, and the specific resistance, k,[1] and its value, according to the foregoing laws, is given by the formula

$$R = \frac{l}{a} \cdot k.$$

[1] The resistance of a conductor, whose length is 1 cm. and whose cross section is 1 sq. cm., is called the *specific resistance* of the substance.

195. **Studies.** — 1. Find the resistance of a German silver wire 100 cm. long, of section .002 sq. cm., the specific resistance of German silver being 21.17 microhms (a microhm is the millionth of an ohm).

$$R = \frac{100}{.002} .00002117 = 1.058 \text{ ohms.}$$

2. Find the resistance of a platinum wire 100 cm. long, and .2 mm. in diameter, the specific resistance of platinum being 9.158 microhms.

3. Find the resistance of a copper wire 125 feet long, and .02 inches in diameter, that of a wire of same material 1000 feet long, and .005 inches in diameter being 424.65 ohms.

4. If 4 voltaic cells, alike in all respects, are joined *in series*, and the internal resistance of each cell is 3 ohms, while the connecting wires are so large and short that their resistance may be neglected, what is the resistance of the battery ?[1]

5. If the same 4 cells are joined *in parallel*, what is the resistance of the battery ?[2]

196. **Strength of Current.** — *a.* If water flows through a pipe at the rate of 100 cubic inches per second, the current is twice as strong as if the rate were only 50 cubic inches per second. Thus the strength of a water current is described by the quantity of water per second which flows through the channel. So *the strength of an electrical current is the quantity of electricity per second which passes along the conductor.*

b. The quantity of electricity in a current is measured in units called *coulombs,* just as the quantity of water in a current is measured in units called *cubic inches.* A current of 10 coulombs per second is tenfold stronger than one of 1 coulomb per second. A current of 1 coulomb per second is called an *ampere,* and this is the practical unit of current strength.

c. Dr. G. S. Ohm in 1827, first pointed out the fact that the strength of any current depends on two things: The electro-

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[1] The internal resistance of a cell is practically the resistance of the fluid between its plates, because the plates being large and good conductors, their resistance is practically nothing.

[2] Plates joined *in parallel* are equivalent to a single plate with a surface equal to the sum of theirs, and hence, practically, they increase the area of the cross section of the fluid through which the current must go.

motive force of the battery or generator, and the resistance of the circuit (§ 193, *e;* § 194, *a*). Ohm's law states that *the strength of current varies directly as the total electromotive force, and inversely as the total resistance of the circuit.* If we let I stand for current, E for electromotive force, and R for resistance, Ohm's law may be written:

$$I = \frac{E}{R}, \text{ or amperes} = \frac{\text{volts}}{\text{ohms}}.$$

Thus: If the electromotive force, E, of a current is 40 volts, and the resistance, R, of the wire which carries it is 5 ohms, then the strength of current, I, is $\frac{40}{5}$, or 8, amperes.

Again: If E is 1 volt, and R is 1 ohm, then I is 1 ampere. Hence we have another definition of the ampere as follows: An ampere is the quantity of electricity which will flow through a resistance of 1 ohm, under the pressure of 1 volt.

197. Studies. — 1. A circuit is made up of a cell, *c*, whose E.M.F. is 2 volts, and whose resistance is .5 ohms; a galvanometer, *g*, whose resistance is 10 ohms; and the wires, *w*, *w*, which connect the two, whose joint resistance is .6 ohms; what is the strength of current? In this case you should see that *Ohm's law* gives[1]

$$I = \frac{E}{R_c + R_g + R_w} \text{ or } \frac{2}{.5 + 10 + .6} = .18 \text{ amperes.}$$

2. A battery of 5 cells *in series*, each cell with E.M.F. of 1.1 volts and a resistance of 3 ohms, is in closed circuit with an outside connecting wire whose resistance is 10 ohms; what is the strength of current in the circuit? *Ans.* .22 amperes.

3. A battery of 5 cells, joined *in parallel*, with E.M.F. of 1.1 volts each, and a resistance of 3 ohms each, is in closed circuit with an outside connecting wire whose resistance is 10 ohms; required the strength of current in the circuit. *Ans.* .1+ amperes.

d. In setting up a battery, *the cells should be joined in series if the external resistance in circuit is large, but in parallel if that resistance is small.* The following examples show the advantage of linking the cells in one or other of these ways,

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[1] We write R_c to stand for the resistance of the cell, c, and so on.

according to the amount of resistance outside. We will first suppose the outside resistance to be large.

1. **Find the strength of current in a wire of 1000 ohms resistance, with 1 cell whose E.M.F. is 2 volts and resistance .5 ohms.**

$$I = \frac{2}{1000 + .5} = .00199 \text{ amperes.}$$

2. **Find the strength of current in the same wire with 100 similar cells joined *in series*.** *Ans.* .190+ amperes.

3. **Find the strength of current in the same wire with 100 similar cells joined *in parallel*.**

$$I = \frac{2}{1000 + .005}. \qquad \textit{Ans. } .00199+ \text{ amperes.}$$

We find that the strength of current through the *very large* resistance is almost 100 times greater with 100 cells *in series* than with one cell, while with 100 cells *in parallel* the current is no greater than with one.

We next suppose the outside resistance to be small.

1. **Find the strength of current in a wire whose resistance is .001 ohms with 1 cell whose E.M.F. is 2 volts and resistance .5 ohms.** *Ans.* 3.99+ amperes.

2. **Find the strength of current in the same wire with 100 similar cells *in series*.**

$$I = \frac{200}{50 + .001}. \qquad \textit{Ans. } 3.99+ \text{ amperes.}$$

3. **Find the strength of current in the same wire with 100 similar cells *in parallel*.**

$$I = \frac{2}{.005 + .001}. \qquad \textit{Ans. } 333+ \text{ amperes.}$$

We find that the strength of current through a *very small* resistance is practically no greater with 100 cells in series than with one, while with the 100 cells in parallel the current is almost 100 times greater than with one.

198. **Measurement of Resistance.** — *a.* We have seen (Experiments 135, 136) how to *compare* the resistance of one conductor with that of another; we are now to learn how to *measure* the resistance in ohms. The apparatus consists of a constant cell

(§ 189, *b*), a galvanoscope, a set of resistance coils, and a key. Fig. 252 represents a "gravity cell" well filled for the purpose. The galvanoscope should be the most sensitive obtainable. An astatic galvanoscope (§ 187, *d*) is best.

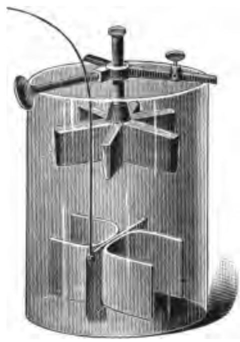

Fig. 252.

b. Resistance coils of wire are used as standards of resistance, just as box-masses are standards of mass. A resistance box contains a set of coils, each of which has a definite and known resistance, which can be put into or taken out of circuit at pleasure. Each coil is made of insulated wire, doubled upon itself, with the two ends fixed to separate brass blocks (Fig. 253), *A*, *B*, *C*, *D*.[1] When brass plugs are inserted, as *a* and *c*, the coils, *L*, *C'*, will not receive the current; but if a plug is out, as *b*, the current must pass through the coil *C*, below, and its resistance is thus thrown into the circuit. A box of coils ranging from 1 ohm, or any other value, upward in regular order, is called a *rheostat*. *AC'B* (Fig. 254) is a

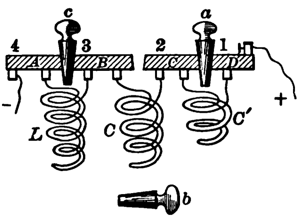

Fig. 253.

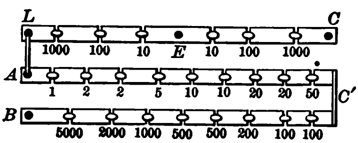

Fig. 254.

diagram of the top of a plug rheostat with the resistances of the coils marked in ohms. Binding posts are found (*A*, *B*) at the ends of the rheostat. The third row, *LC*, is no part of this

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[1] The winding of the coil double is to neutralize the self-induction (§ 216) as far as possible.

rheostat, but accompanies it to be used as a part of a Wheatstone bridge (*c*).

Fig. 255 represents one form of key. The circuit is closed by pressing the knob.

Fig. 255.

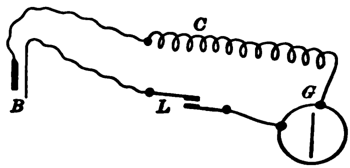

Fig. 256.

Experiment 187. — *Object.* To measure the resistance of a given wire by the *method of substitution.*

Connect the battery, *B*, the key, *L*, the given resistance, *C*, and a galvanoscope, *G*, in series as shown (Fig. 256). Note the reading of the galvanoscope carefully. Put a rheostat *in place of the resistance, C, without disturbing the cell or galvanoscope.* Remove plugs until, by trial, you obtain the same deflection of the needle as before.

The sum of the resistances in circuit will be equal to the resistance of the given wire, because equal resistances reduce the strength of a current equally, and equal strengths of current produce equal deflections. Repeat the work and take the average value. The greatest danger of error lies in the battery; if the cell is not *constant*, the results are worthless.

c. The best method of measuring resistance is carried out by means of a *Wheatstone bridge.* The principle of the bridge is that of a *divided circuit.* Thus a current in a wire, *L* (Fig. 257), finds at *A* two conductors leading to the point *B*, where they unite in one. This is a divided circuit. In such a case the current will divide at *A*, and *the parts which traverse the two paths will be inversely as the resistances of the conductors* (§ 194, *a*).

d. But we have seen that the point toward which a current goes, has a lower potential than that from which it goes. Thus *B* (Fig. 257) has a lower potential than *A*. In fact, every point along the way from *A* to *B* must have a lower potential than the one behind it. This gradual lowering of potential between two places is described as the *fall of potential.*

Since the potential must fall just as much between A and B on one path as on the other, there must be for every point, C, on one conductor *some* point, C', with an equal potential on the other. In that case if a wire should bridge across from C to C', no current would flow through it. The most sensitive galvanoscope could be joined to C and C' without being affected by the strongest current from L, provided these two points have equal potentials, and they will have equal potentials if the resistances of the four parts of the divided circuit are properly adjusted. The *facts* as to this adjustment are as follows:[1]

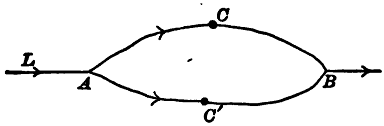

Fig. 257.

e. Thus Fig. 258 represents a circuit divided at A, reuniting at D. Let M stand for the resistance of the conductor, AB, N for that of AC, O for that of BD, and P for that of CD. Then if these resistances are *so adjusted* that

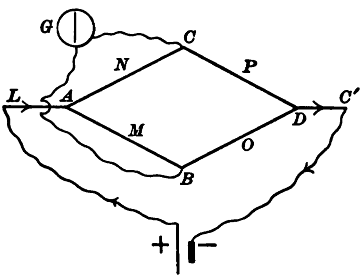

Fig. 258.

$$M : N :: O : P,$$

the points C and B will have equal potentials, and no current will flow through the galvanoscope, G, which connects C and B. *When this is the case, if the three resistances, M, N, and O, are known, the fourth, P, can be computed.*

f. There are two forms of Wheatstone bridge, — one known as the *coil bridge*, the other as the *wire bridge*.

The coil bridge (Fig. 259) consists of three sets of resistance

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[1] Advanced students may find the *theory* in Carhart's *University Physics*, pp. 278–280.

coils, corresponding to *M*, *N*, and *O*, to which can be joined the unknown resistance which corresponds to *P*. Patiently compare Fig. 259 with Fig. 258. The same letters represent corresponding parts.

Observe also that the battery, *B*, and the galvanoscope, *G*, are connected with corresponding parts in the two figures. A key, *K*, is added in Fig. 259. The two conductors, *AB* and *AC*, are called the *arms* of the bridge, and the third, *O*, is called the *rheostat*. Notice that the resistance in the arms can be made equal, or one of them 10 or 100 times the other, by the removal of plugs.

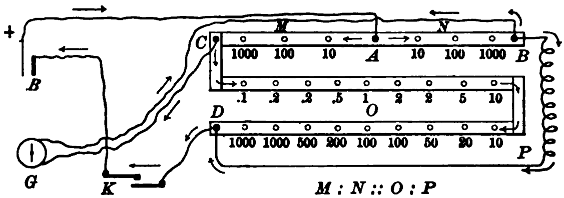

Fig. 259.

g. To illustrate the method of measuring a resistance: *P* (Fig. 259) was a coil of wire whose resistance was unknown. *M* was made 100 ohms, and *N* 10 ohms, and then by trial it was found that no deflection in the galvanometer occurred when the sum of the resistances in *O* was 25 ohms. Since $M : N :: O : P$ (*e*), we have, for the resistance of *P*,

$$100 : 10 :: 25 : P. \quad \text{Hence } P = 2.5 \text{ ohms.}$$

If *M* had been made 10, *N* 1000, and if *O* had been found to be 25 ohms, then the resistance, *P*, would have been found by the proportion $10 : 1000 :: 25 : P$, to be 2500 ohms.

Experiment 188. — *Object.* To find the resistance of 5 m. of No. 24 German silver wire to within one ohm.[1]

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[1] Other conductors may be chosen, but they should be precisely described in the notebook.

The wire, P, should be joined by connectors to the ends of heavy wires, a and b (Fig. 260), whose resistance may be neglected, and by these to the bridge at D and C. Its length is to be measured carefully from the outsides of those connectors; hence cut it 4 cm. longer than the 5 m., and push 2 cm. of each end through a connector. Let the wire be supported by winding around two heavy bottles, E, F, so that it shall not touch itself at any point. Join the battery to A and D with a key, as shown. Join the galvanoscope, G, to B and C. Put K and G near the front of the table, so that while the left hand manages the key you can place the eye directly over the scale of G.

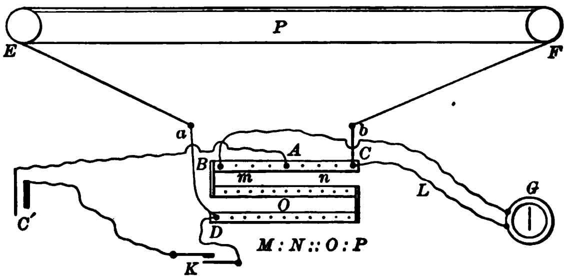


Fig. 260.

The galvanoscope should be as far from P as practicable, so that it shall not be affected by the current in that wire, and its leading wires, L, should be parallel, as shown, so that it shall not be affected by the current in them.

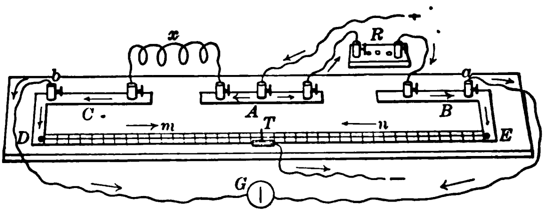
It is best to *make a preliminary test* as follows: Make M and N equal. Remove the first plug of the rheostat; press K, and note the *direction* of the swing of the needle, G. Restore the plug; remove the last plug of the rheostat; press K, and note the direction of the swing. The swings should be in opposite directions. If they are not, either the resistance of P is greater than any contained in the bridge, or the connections are wrong. Examine the connections. If they prove to be right, try another ratio in the arms; make M ten times N, and repeat the operations. If then the swings are in opposite directions, you have all the conditions for measuring P; but if not, make M one tenth of N and try again. But let us suppose that $M = N$.

Now proceed to put into the circuit one resistance after another by removing plugs from the rheostat, watching the needle after each change, remembering which way it swings for *too much* and for *too little*, until, with the addition of a one-ohm coil the swing indicates "too much," while without it the swing indicates "too little." The sum of the rheostat resist-

ances is the value of O, and, since $M = N$, O must equal P to within one ohm. Time and confusion are saved by removing the plugs in systematic order in the same way that box-masses are placed on the pan of a balance (§ 5, *f*).

h. The *wire* or *meter bridge*, with its connections, is shown in Fig. 261. Upon a base of varnished wood are two L-shaped strips of copper, B, C, and between these is a straight piece, A. A German silver wire extends from D to E, with its ends soldered to the L-shaped strips. It lies upon a scale graduated to millimeters. T is a *sliding contact*, — a wire fixed in a block which may slide along DE. These parts constitute the bridge.

The *connections* are as follows: One pole of the battery joins the middle binding post of A, and the other joins the sliding



— $x : R :: m : n$ —

Fig. 261.

contact, T. The galvanometer, G, joins the two L-shaped strips of copper at a and b. A rheostat, R, connects the adjacent binding posts of the two strips B and A; and the body x, whose resistance is to be measured, connects the adjacent posts of C and A. The course of the current should be traced through the circuit by help of the arrows.

The *operations* to measure a resistance, x, consist in, *first*, removing plugs, to insert a known resistance at R. This should be as nearly the resistance of x as it is possible to estimate. *Second*, finding by trial where T must be placed on the wire to cause no deflection of the needle of the galvanom-

eter; *third*, reading the lengths of the parts of the wire, DT and ET. The value of x is then found by the proportion

$$x : R :: m : n.$$

Experiment 139.—*Object.* To verify the following law: *The resistance of a conductor of uniform cross section and material is directly proportional to its length* (§ 194, *c*).

Apparatus: A wire bridge (Fig. 261). The mounted resistance wires (Fig. 251). A constant cell. A key. A galvanoscope. Connect the battery, galvanoscope, and rheostat with the bridge as in Fig. 261, placing a key in the battery circuit. Then in place of x put the wire aC (Fig. 251). Large wires must be used to connect R and x with the bridge, so that their resistance may be very small (§ 194, *c*, 2).

Shunt the galvanometer (§ 187, *f*); this is very important. Remove a plug from the rheostat, and proceed as follows: 1. Place the sliding contact, T, near the end, E, of the wire; the galvanometer will be deflected, let us say, to the left. Then place T near D; the deflection should be to the right. This will show that the connections are all right. 2. Find where T must be placed to make the deflection small; then take off the shunt, and very carefully obtain the position of T for no deflection. Note the values of R, m, and n.

Make the wire 2 m. instead of 1 m. long, by connecting posts a and b (Fig. 251) with the bridge, and again find the place of T for no deflection. Compute the two resistances, and see if they accord with the law stated.

Experiment 140. — *Object.* To verify the following law (§ 194, *c*, 4): *The resistance of a metallic conductor depends on its temperature.*

Method. Measure the resistance of a copper wire at 0° C. and at 100° C. by the wire bridge.

Apparatus. A Hall's temperature coil, and a wire bridge with all its necessary accessories (Fig. 261). The coil (Fig. 262) consists of a long, fine, copper wire, wound in a groove around a hollow cylinder of hard rubber, open at the bottom. It terminates in two large wires, W, W, by which to connect it with the bridge. A thermometer, T, is inserted through the cap to show the temperature.

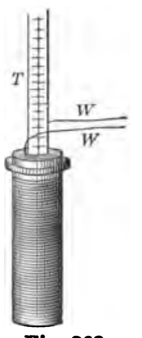


Fig. 262.

Operations. Insert the coil in a beaker of ice water, and when the temperature has become stationary at 0°, keep it so as nearly as possible, while you connect the coil to the meter bridge in place of x, and proceed as in Experiment 138 to measure its resistance to the nearest ohm. Denote this resistance at 0° C. by R_0.

Insert the coil in a beaker of water, and keep it at 100° C. as nearly as possible while you measure its resistance again to the nearest ohm. Denote this resistance of the coil at 100° C. by R_{100}. If you find R_{100} distinctly larger than R_0, the statement in regard to the effect of heat on resistance is verified.

From the results of Experiment 140, we may find what is called the *temperature coefficient* of resistance of copper. The temperature coefficient is the amount of change, per ohm, in the resistance of the conductor at 0°, caused by 1° C.

What computations are necessary, and the reasons for each step, may be stated as follows:

The total *resistance* at 0° C. has been found . . .	R_0	ohms
The total *resistance* at 100° C. has been found . .	R_{100}	"
∴ total *change* in R_0 ohms for 100° C. =	$R_{100} - R_0$	"
∴ total *change* in 1 ohm for 100° C. =	$\frac{R_{100} - R_0}{R_0}$	"
∴ the *change* in 1 ohm for 1° C. =	$\frac{1}{100} \times \frac{R_{100} - R_0}{R_0}$	"

Carry this computation through with your values of R_{100} and R_0 to find the temperature coefficient of copper.

199. **Measurement of Electromotive Force.** — *a.* The practical *unit* of E.M.F. is the volt. The *standard* (§ 2, *b*) is a cell whose E.M.F. is accurately determined.[1] A Daniell cell[2] has an E.M.F. of very nearly 1 volt, and is approximately constant. We shall use a Daniell cell of the gravity form (Fig. 252) as the standard in our experiments, but inasmuch as its E.M.F. is not exactly 1 volt, let us call it, for the present, "1 Daniell."

b. The facts on which one method (Wheatstone's) of measuring E.M.F. is founded are:

1. The electromotive forces of two cells are to each other as the two resistances which produce equal diminutions of the strength of current.

2. Equal diminutions of the strength of current are shown by equal diminutions of the deflections of a galvanoscope needle.

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[1] The Latimer Clark cell has been adopted as the international standard. See Carhart's *University Physics*, Part II., p. 251.

[2] Carhart's *University Physics*, p. 241.

If E' stands for E.M.F. of the given cell, and E for that of the standard, while R' and R stand for the resistances which will reduce the swing of the same galvanoscope needle by the two cells equally, the first of the above facts declares that

$$E' : E :: R' : R; \therefore E' = E \cdot \frac{R'}{R}.$$ [1]

Experiment 141. — *Object.* To find the E.M.F. of a given cell by comparison with a Daniell.

Join the Daniell cell, C, a rheostat, R, a galvanoscope, G, and a key, K, in series as shown (Fig. 263). Insert resistance by removing plugs until you get a deflection, d, of about 45°. Note this resistance, and designate it r. Then insert additional resistance enough to reduce the deflection any convenient number of degrees, say 10. Designate this resistance by $r + R$. Next put the other cell in place of C, and insert resistance to produce the same deflection, d. Designate this resistance by r'. Insert resistance to reduce the deflection the same number of degrees as before. Designate it by $r' + R'$. These operations should be repeated two or three times. Record the observations in tabular form, thus:

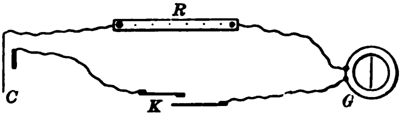

Fig. 263.

Observations.					Computations.	
Trials.	r	$r+R$	r'	$r'+R'$	R	R'
——	——	——	——	——	——	——
——	——	——	——	——	——	——
——	——	——	——	——	——	——
				Average	——	——

Then by substitution in $E' = E \cdot \frac{R'}{R}$ you can find how many "Daniells" there are in the E.M.F. of the given cell.

If the value of 1 Daniell is known, the E.M.F. of the other cell is found in volts by multiplying. Let the Daniell be 1.08 volts, and the

[1] For proof of this principle see Chute's *Physical Laboratory Manual*, p. 129.

mean of your results for the other cell be 1.8 Daniells; then the E.M.F. of the other cell is $1.08 \times 1.8 = 1.9$, volts.

c. The E.M.F. of a current may be measured with facility by means of a *voltmeter*. A voltmeter is a galvanometer which shows the E.M.F. directly in volts. There are several varieties, but all forms agree in this: 1. The coil has a very high resistance, so that little current will be transmitted. In this case the deflection is proportional to the E.M.F.

This fact appears from a study of Ohm's law (§ 196, *c*). Let r stand for the internal resistance of a circuit and R for the external resistance. Then $I = \frac{E}{r + R}$. Now if R is *very great* in comparison with r, then I will be affected *very little* by changes in r, and I will vary directly as E. Hence the deflection of the needle will stand for the E.M.F., and the scale divisions indicate volts.[1] The potential difference between any two points can be measured in the same way.

Fig. 264 represents a *Weston's* voltmeter. To measure the E.M.F. of a cell, the binding posts, A, B, are connected with

Fig. 264.

the poles of the cell; the pointer swings at once to the scale number showing its value in volts.

[1] The voltmeter is *calibrated*, that is graduated, to indicate volts, by marking the positions of the pointer when 1, 2, 3, and other numbers of volts are actually used.

200. Measurement of Strengths of Current. — *a*. One method of finding the strength of a current is carried out by means of an *ammeter*. An ammeter is a galvanometer which shows the strength of a current directly in amperes. There are several varieties, but all forms agree in this: The coil has a very low resistance, so that it will not sensibly reduce the current which it is to measure. In this case the deflection is proportional to the strength of current. This will appear from a study of Ohm's law as above, by taking $R = 0$. Hence the scale divisions indicate amperes. To measure a current it is only necessary to send it through the ammeter; the pointer at once swings to the number of amperes.

b. Another method of finding the strength of a current consists in measuring both the E.M.F. and the resistance, and substituting these values in Ohm's formula, $I = \frac{E}{R}$ (196, *c*). Thus if with a Wheatstone bridge the resistance in a circuit is found to be 5 ohms, and with a voltmeter the E.M.F. is found to be 17 volts, the formula gives $I = \frac{17}{5}$, or 3.4, amperes.

c. Still another method is carried out by means of a tangent galvanometer. If we wish only to *compare* two currents, we obtain deflections by one and then the other, and find the tangents of these angles in a table of natural tangents. The ratio of these tangents will be the relative strengths of the currents. Thus two deflections were found to be 15° and 45°. A table gives the tangent of $15° = .268$, and of $45° = 1.000$. Then if I and I' stand for the strengths of the two currents, we have, by the law of tangents (187, *e*),

$$I : I' :: .268 : 1.000 \text{ or } :: 1 : 3.73.$$

That is, the strength of one current is 3.73 times that of the other.

If we wish to *measure* a current, we would, after finding the tangent of the deflection, convert it into amperes, by multi-

plying it by a certain number, called the *constant* of the galvanometer. This constant must be found by experiment for each galvanometer.

201. **Measurement of Other Quantities.** — Every electrical quantity, whether it relates to currents, to static charges, or to magnets, can be measured, but for the methods and apparatus employed the student is referred to laboratory manuals devoted to the methods of experimental work.

MAGNETS AND THE MAGNETIC FIELD.

202. **Magnets.** — *a.* One of the most important properties of certain bodies, called *magnets*, is revealed by the following experiment:

Experiment 142. — In Fig. 265, CC' represents a slender rod of iron, with many turns of insulated copper wire, No. 20, wound around it, leaving only the ends bare. L is a block of wood with two semicircular grooves filled with mercury. The rod is balanced on the end of a thread of untwisted silk, and suspended from above so that the ends of the wires, w, w, just penetrate the mercury. The block, L, is carefully adjusted so that when the rod swings, the wires will follow the semicircular mercury cups.

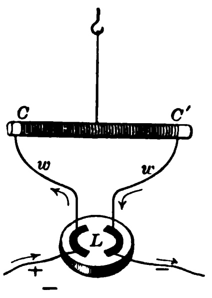

Fig. 265.

The rod should rest equally well in all positions. Place it east and west. Then put one terminal of a voltaic cell into each mercury cup. The rod should swing into a line nearly north and south, and refuse to rest in any other position while the current is on. This shows that the rod has become a magnet.

A magnet is a body which, if perfectly free to move, will rest in one position only. Its axis will be directed nearly north and south.

b. Magnets differ from other bodies in another respect, which is revealed by the following experiment: they attract iron in preference to other metals.

Experiment 143. — Send the current again around the rod CC' (Fig 265), and then put small iron nails or tacks in contact with the ends of the magnet. A tuft of these bits of iron should cling to each. Try bits of copper wire and of other substances. *The power to attract iron* is a characteristic property of magnets.

Magnets are bodies which attract iron in preference to other metals.

203. **Natural and Artificial Magnets.** — *a.* One of the richest ores of iron is called *magnetite.* Certain specimens of this ore are natural magnets. They attract iron, in preference to other metals, and will not rest when suspended, except when certain points are directed north and south. This mineral is the *lodestone* of the ancients, who used these natural magnets to direct their ships at sea.

b. Artificial magnets are made of iron. Bars of soft iron may be temporarily magnetized or converted into magnets by the action of an electric current (Experiment 142). Bars of hard iron or steel may be permanently magnetized in the same way, or by stroking them repeatedly in one direction with one end of a magnet (Experiment 14).

Experiment 144. — *Object.* To magnetize a darning needle. Use the rod and coil CC' (Fig. 265).

1. Magnetize the rod as in Experiment 142. The ends of the wires, *w*, *w*, would better be joined directly to the terminals of the cell, and the rod and coil held in the hand.

2. Draw the darning needle from point to eye across one end of the rod repeatedly, and keep it at a distance while carrying it back each time. That the needle has become a magnet you can prove, because it will point north and south if suspended, and lift small nails or a tuft of iron filings to which either end is presented. Try it.

3. Now heat the needle red-hot, and try it with the nails again. Then anneal it as thoroughly as possible (§ 42, *d*), and try to magnetize it. Finally temper it very hard (§ 42, *c*) and try again. What inferences can you draw from these experiments?

c. Artificial magnets retain their magnetic properties for a short or long time, depending on the quality of the iron of which they are made. Pure soft iron remains a magnet only

while the magnetizing action lasts; such are called *temporary magnets.* Hardened iron and steel retain their magnetic properties for a long time; such are called *permanent magnets.* Permanent magnets are made of hardened steel.

204. **Polarity.** — *a.* Whether the attraction for iron is the same at all points of a magnet is shown by the following experiment:

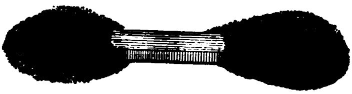

Fig. 266.

Experiment 145. — Spread iron filings on a sheet of paper, and bring the whole length and all sides of a magnet into contact with them. Where the attraction is stronger the more filings will cling, and the unequal distribution of the force will thus be revealed (Fig. 266).

b. The two opposite points of a magnet, where the attraction is most concentrated, are called its *poles.* The line joining the poles is called the *axis.* It is this line which lies nearly north and south when a magnet is suspended, and the end which is directed northward is called the *north-seeking,* or, more briefly, the north or + pole, while that which is directed southward is called the *south-seeking* or south or − pole of the magnet.

c. In the mutual action of magnets a law similar to the law of attraction and repulsion of electrified bodies prevails (172, *f*, *h*).

Experiment 146. — *Object.* To discover the law of magnetic attraction and repulsion, and to identify the polarity of a magnet.

Two magnets are required. Suspend each and mark its N-seeking pole. Then, leaving one of them suspended, present to its north pole first one and then the other pole of the other magnet, and note the action. In the same way present the poles to the south pole of the suspended magnet. Compare your results with the following statement:

d. Poles of the same name repel each other, and those of different names attract each other. This is the first law of magnetic attraction and repulsion.

This law shows us how we may learn which is the north

and which the south pole of any magnet without suspending it. For if we have one which is already suspended, we need only to present one pole of our magnet to one pole of the suspended magnet and observe whether there be attraction or repulsion.

e. All substances are either attracted or repelled by a magnet, but in most cases the action is extremely feeble. Substances which are attracted are called *paramagnetic*, and those which are repelled, *diamagnetic substances*. The latter are far more numerous and their effects are more feeble. But a magnetic substance of either class differs from a magnet. Magnets have poles; magnetic substances have no poles. Iron, for example, is attracted alike by both poles of a magnet, and bismuth is repelled by both poles alike.

205. **The Magnetic Field.** — *a.* The space around a magnet, in which attraction or repulsion is exhibited, is called the *magnetic field*, just as the space around an electrified body is called the *electric field* (§ 173, *b*). A piece of soft iron placed in the magnetic field is under magnetic influence and becomes a temporary magnet. To study this action, proceed as follows:

Experiment 147. — *Object.* To study the action of a magnet upon soft iron placed in its field (1) when the two are not in contact; (2) when the two are in contact.

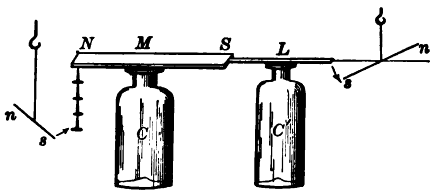

Fig. 267.

I. Fig. 267 will suggest to you how to study the effect of contact by either one of two methods.

1st method: *M* represents a strong magnet.
L, a rod of iron touching the south pole of *M*.
ns, a magnetic needle to test the polarity of *L*.

2d method: *M* represents a strong magnet.
A, small nails supported by the attraction of unlike poles. Each nail in the chain is a magnet. The polarity at the end of the chain *A* may be tested by the needle *ns*.

II. Place a strong magnet upon a convenient support (Fig. 268), and hold a rod of soft iron — it may be a wrought-iron nail — with one end very near the north pole. Bring a card strewn with iron filings up against the rod. If the rod has become a magnet, little tufts of filings will cling to its ends. Or small tacks will cling, as shown, to the ends, but fall from the middle of the rod. It may be proved that the end of the rod nearest the pole of the magnet is a pole of opposite kind, while the distant end is a pole of the same kind. Repeat, with the rod in the field of the south pole.

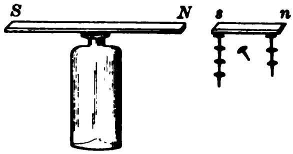

Fig. 268.

b. The magnetization of a body when placed in a magnetic field is called *magnetic induction*. The law of magnetic induction is similar to that of electric induction (§ 177, *a*, *b*). It states that *either pole of a magnet induces a pole of unlike kind in the nearest part of a piece of iron in its field, and a pole of like kind in the most distant part.*

This law prevails even when the iron is in contact with the pole.

c. There is never any transfer of magnetism from a magnet. One magnet affects another, or develops polarity in iron, always by induction, never by conduction. Each nail in the chain *A* (Fig. 267) has been magnetized by the magnet *M*, but *M* has lost none of its magnetism. Every iron filing in the tuft which clings to the pole of a magnet (Fig. 266) has become a magnet, and they all cling together by the attraction of their unlike poles, but the magnet in whose field they become such has lost nothing. The fact is that the magnet produces a magnetic stress in its field, which magnetizes the iron, but the field is produced whether the iron is present or not.

d. To explore the field we may use a short *test needle* (Fig. 269), made of a piece of magnetized watch spring, not more than 1.5 cm. long, pierced with a hole at its center, through which passes a smaller thread of glass, with a knob, *C*, on the end to keep the needle from falling off. If the magnetic force in the field is in any one direction rather than another, this little needle will point it out.[1]

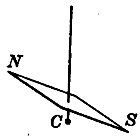

Fig. 269.

Experiment 148. — *Object.* To explore the field of a magnet by means of a test needle.

Place the test needle at *a* (Fig. 270). It will swing into line as shown, with its north pole pointing away from N. Carry it away, making its center move in the direction in which *N* points. Its path will be apparently a straight line, as shown by the arrow. Place the test needle alongside the north pole of the magnet. Move it slowly, taking care to keep its center going, at every point, in the direction in which its north pole points. It will be found to follow a curved line, which finally terminates in the south pole of the magnet, as shown. Start from one or another corner of the magnet, and observe the curved path which the center of the test needle pursues. In starting from the south pole of the magnet, the south pole of the test needle will, of course, go ahead. Evidently *the magnetic force* is in curved lines, and *has a definite direction at every point in the field.* These directions, in which a north pole of a magnet is impelled through the field, are called *lines of force*, or *lines of induction.*

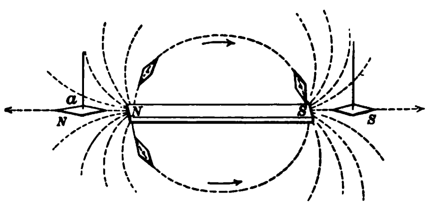

Fig. 270.

e. To map the field of a magnet, and make the directions of the lines of induction visible, iron filings may be used. Every filing becomes a magnet by induction, and clings to a neighbor by the attraction of unlike poles. Each line of filings formed in this way lies along a line of induction through the field.

[1] A short magnet suspended by silk fiber is not so good, because it will swing bodily in various directions.

Experiment 149. — *Object.* To map the field of a magnet by means of iron filings.

Place a sheet of glass or of stiff cardboard flat upon a straight or bar magnet. Sprinkle fine iron filings from a fine sieve or muslin bag upon the sheet, gently tapping it meanwhile to facilitate the movement of the

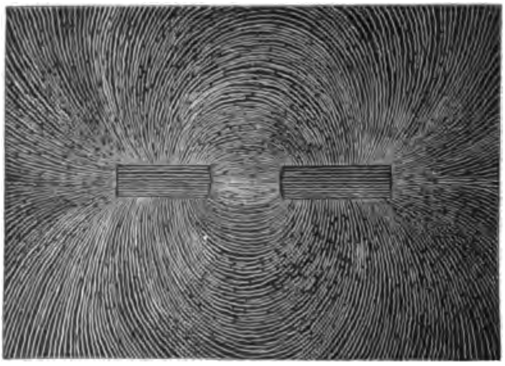

Fig. 271.

filings into the places assigned to them by the magnetic force. Fig. 271 represents faithfully the *lines of force* all around a certain magnet in a horizontal plane. The same arrangement exists in every possible plane, vertical or oblique.

Repeat Experiment 148, with the test needle placed above the sheet of iron filings as it still lies upon the magnet. Does it follow the lines on the map?

f. The strength of the field is greatest at points in contact with the poles of the magnet. This is shown in the map (Fig. 271) by the crowding of the lines together, while their separation, more and more, as the distance increases, indicates the diminishing strength of the field.

g. The *direction* of the lines of force in the field depends upon the *form of the magnet* and the names of the adjacent poles.

As to form, magnets are generally either *bar magnets* or *horseshoe magnets*, according to whether they be straight or bent into the shape of a horseshoe or letter U. The field

of a bar magnet is shown in Fig. 271. The field of a horseshoe magnet is shown in Fig. 272. Between the poles the lines of force are straight and parallel; in front of them the lines spread out in wide curves.

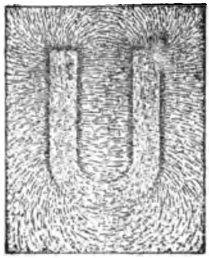

Fig. 272.

Fig. 273 represents the field between the unlike poles of two bar magnets. Mutual attraction exists in this case. The field between the like poles of two bar magnets is shown in Fig. 274. Mutual repulsion exists in this case.

h. The strength or *intensity* of the field at any place depends on the strength of the pole of the magnet and the distance from it. To *represent* a field of great intensity, the lines of force are to be drawn in the diagram very near together, and farther apart to represent lesser intensity. Now it is agreed that *one line shall be drawn to represent a force of one dyne.* So in every part of the field the number of lines in a square centimeter represents the number of dynes of magnetic force per square centimeter. The *unit* strength of field is represented by one line per square centimeter of cross section. This unit is called a *gauss.*

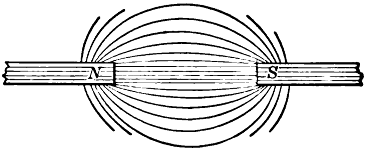

Fig. 273.

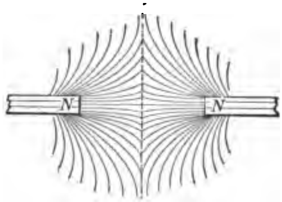

Fig. 274.

i. The best way to become acquainted with the magnetic field is to use iron filings, as in Experiment 149, making many different arrangements of magnetic poles, and studying the figures carefully with reference to the *direction* and the *intensity* of the field at all points.

206. **Permeability.** — *a.* It is found that the number of lines per square centimeter, in the magnetic field, depends on the kind of matter through which they have to pass. In the same field, iron, for example, transmits the lines of force more freely than air. And that property of matter which determines what proportion of the lines of force in a magnetic field shall enter it is called *permeability.*

b. Let *N*, *S* (Fig. 275) represent the parallel faces of two unlike poles, with a *vacuum* between. The field directly between *N* and *S* is *uniform,* — that is, the lines are parallel and equally spaced, — and its intensity, or number of lines per square centimeter, depends on the strength of the poles. In air the intensity of field would not be perceptibly changed; that is to say, the permeability of air is practically the same as that of free space. The same is true of glass, and wood, and many other substances.

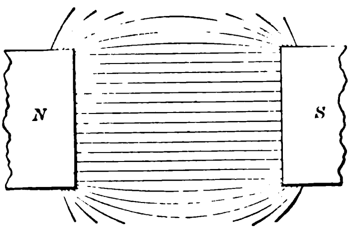

Fig. 275.

c. Let a ball of iron be placed in the uniform field between *N* and *S*. The field at once ceases to be uniform. The lines of force take to the iron in preference to air (Fig. 276), and the number per square centimeter is greater in the iron than in the air. That is to say, the permeability of iron is greater than that of free space or of air. The same is true of all *magnetic substances.*

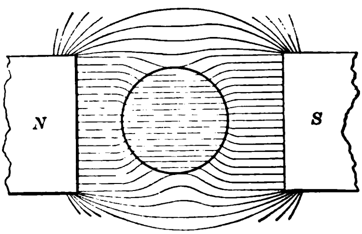

Fig. 276.

d. Let a ball of bismuth be placed in the uniform field. Again the field ceases to be uniform. The lines of force seem reluctant to enter the bismuth, preferring air (Fig. 277),

and the number per square centimeter is less in the bismuth than in air. That is to say, the permeability of bismuth is less than that of free space or of air. The same is true of all *diamagnetic substances* (§ 204, *e*).

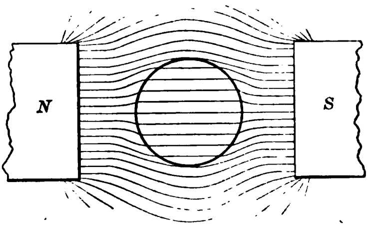

Fig. 277.

e. Permeability is precisely defined for each substance as the ratio of the number of lines per square centimeter in the substance to the number per square centimeter in air. For example: A certain specimen of iron, when placed in a magnetic field with 50 lines per square centimeter in air, was found to contain no less than 16,062 lines per square centimeter (Thompson). Now dividing 16,062 by 50 gives 321; that is to say, the permeability of the iron is 321.

f. But there is a limit to the number of lines which can be received by any substance. The practical limit for good wrought iron is about 20,000 per square centimeter; for cast iron, about 12,000; while steel will take 16,000. Hence, other things being equal, *stronger* magnets can be made of wrought iron than of cast iron or steel. A magnet is said to be *saturated* when it contains all the lines of force which it is capable of transmitting.

g. The obstruction which a substance offers to the lines of magnetic force is called *reluctance*. It is the opposite of permeability, and is analogous to the resistance of conductors. Thus the permeability of bismuth is less than that of iron; its reluctance is correspondingly greater.

207. **The Magnetic Circuit.** — *a*. We have seen that a north pole of a test needle (§ 205, *d*), starting from the north pole of a magnet, describes a curve through the field around to the south pole, as if it were floating in a magnetic stream. A south pole

describes a curve around to the north pole in the same way. To study this twofold action it is not necessary to consider both directions all the time, and it is agreed to assume that *the lines of force go out from the north pole and reënter the magnet at the south pole.*

The effect is the same as if magnetic streams were flowing continually through the magnet, going out at the north and spreading through all surrounding space in curved paths back to reënter the south pole, every line in all the field making a complete circuit, as some are shown to do in Fig. 278. These continuous lines of force, through a magnet and back through air or other bodies outside, are called the *magnetic circuit.* In the case of the horseshoe magnet (Fig. 272), the circuit extends from the south pole around through the magnet to the north pole, and it is completed through the air over to the south pole, from which they are supposed to start. The iron filings in Experiment 149 render these lines visible.

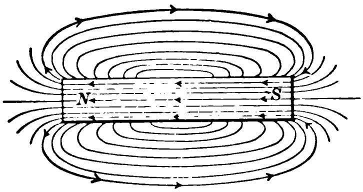

Fig. 278.

b. If the magnet is provided with an *armature,* that is, a bar of soft iron reaching from pole to pole, then the circuit is completed through the armature rather than through the air (Fig. 279), because of the greater permeability of the iron.

c. Magnetic action passes through glass, wood, brass, and many other substances just about as freely as through air. These substances are said to be *transparent* to magnetic lines of force, as water is transparent to waves of light. In Fig. 280 a wooden ring, *W*, is supposed to be in the air space between the poles N and S,

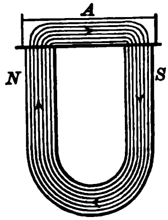

Fig. 279.

and a few of the lines of force are shown passing directly through the wood and the air space within the ring.

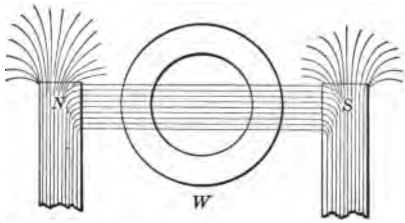

Fig. 280.

d. But a mass of iron in the air space between the poles of a magnet becomes itself a part of the magnetic circuit. The lines enter the mass at the points nearest the north pole, follow the metal to points nearest the south pole, where they emerge on their way in the circuit. In Fig. 281 a soft iron ring is supposed to be in the field, and the courses of a few lines are represented. They are diverted from straight lines and leave

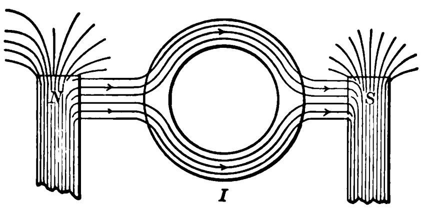

Fig. 281.

the air space within the ring vacant. The ring is a screen shutting out the magnetic action of the poles from the space it incloses. The space inside a hollow ball of soft iron is effectually shielded from magnetic force. A sensitive magnet suspended in a closed soft iron box cannot be affected by magnets outside. Watches are in this way protected from the magnetizing influence of strong currents.

208. **The Molecules are the Real Magnets.** — *a.* There are many reasons to believe that every molecule of iron is a magnet, one side being a + pole, the other side a − pole. One indication of this is found in the following fact: Let a magnet be broken at its center, and each half is found to be a complete magnet, both ends being poles and the middle point neutral; while if reunited, the new poles again become neutral. Let either half be broken, and each piece has its N and S pole; and if the breaking be carried along until the pieces are as small as practicable, still each is a magnet. It is fair to infer that if we could carry the division further, the same thing would be true even to the smallest possible piece, which is the molecule.

b. Magnetized iron is supposed to differ from unmagnetized iron in this way: Its molecules are systematically arranged with their unlike poles together, so that all the north poles are directed toward one end of the bar, and all the south poles toward the other end, while in the unmagnetized bar the molecules lie with their poles promiscuously in all directions. So in iron the attraction, and the repulsion too, is as much in one direction as another, while in the magnet the attraction is all directed toward one end and the repulsion all toward the other. Hence these forces grow stronger and stronger toward the ends. *The action of a magnet is therefore the resultant of all the magnetic forces seated in its molecules.*

c. But it is easy to see that the surface molecules of a magnet are not in the same condition as those of the interior. Every interior molecule of iron is entirely surrounded by others, while the surface molecules are exposed on one side to air. Hence the poles of every interior molecule are fully engaged with its neighbors, while those of the surface molecules are not; and so there is a residue of magnetism at the surface to affect iron or magnets outside. *The molecular fields within are neutralized, while those at the surface are not.* The

magnetism in the surface molecules of a magnet which is not neutralized by the interior molecules, is called *free magnetism.*

209. **Magnetic Needles.** — *a.* A magnetic needle is a slender bar magnet supported in such way that it may move freely in obedience to magnetic forces. Practically, there are three kinds of support. It may be supported upon a pivot (Fig. 282). In this case the free motion is in a horizontal plane only.

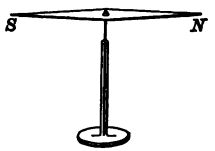

Fig. 282.

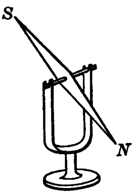

Fig. 283.

Such horizontal needles are used in the mariner's and the surveyor's compass. The needle may be supported upon a horizontal axis (Fig. 283). In this case the free motion is in a vertical plane only. Such needles are called *dipping needles.* Finally, the needle may be suspended by a small thread or hair fixed upon its middle point. In this case the free motion is in all planes.

b. To make a horizontal magnet, the needle must be magnetized first and then balanced upon its pivot. The pivot will not be in the center of mass of the needle exactly, unless the needle is at the magnetic equator of the earth. At all points north of the equator the south end of the needle will be the heavier, and at all points south of the equator the north end will be heavier than the other. But the needle will be horizontal when it is supported.

To make a dipping needle, it must be balanced first and magnetized afterwards. Then the point of suspension will be in the center of mass; there will be equal weights on opposite sides of it, but in the northern hemisphere the N-pointing pole

will seem to be the heavier, while the S-pointing pole will seem to be the heavier in the southern hemisphere.

210. **The Earth is a Magnet.** — *a.* The behavior just described, of magnetic needles in different places, leads to the conclusion that the earth is itself a magnet. That the earth affects a magnetic needle as another magnet affects it, is verified by the following experiment:

Experiment 150. — 1. Place a long bar magnet, *NS* (Fig. 284), upon the table. Suspend a short needle, *ns*, by a fiber. Carry the needle to a point directly over *N*, and observe the position it takes in obedience to the magnetic force at that part of the field. Then carry the needle slowly, still in the vertical plane, along to a point directly over *S*, noting its changes of position in the field.

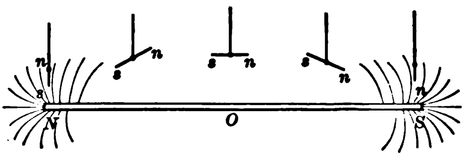

Fig. 284.

The fact is that the needle will lie with its length tangent to the line of force which passes through its center wherever it is placed. On this account it is vertical when above *N* or *S*, horizontal when over the middle of *NS*, and inclined with its south pole downwards toward *N*, and its north pole downward toward *S*.

2. Next place the needle on a level with the magnet and a little to one side, and see that it swings horizontally, its south pole toward the axis of the magnet if it is between *N* and *O*, but its north pole toward the axis if it is between *S* and *O*.

On a large scale, a dipping needle, when carried to places north and south of the equator of the earth, behaves like the needle in 1 of the foregoing experiment, and a horizontal needle behaves as did the needle in 2.

b. But the magnetic north pole of the earth does not coincide with the geographical North Pole; it is more than 1000 miles away from that point. It was found, in 1831, by Sir J. C. Ross, in latitude 70° 5′ N. and longitude 96° 46′ W. The magnetic south pole of the earth has not yet been discovered.

c. The magnetic needle in the northern hemisphere points its north pole toward the magnetic north pole, and not toward the geographical North Pole. The variation of the needle from the geographical north and south line at any place, is called the *magnetic declination.*

But there are places at which there is no declination. If a line were drawn through all such places in North America, it would enter the continent on its way from the south pole at a point near Charleston. Its general course would be northwesterly, passing through the Carolinas, the western parts of the Virginias, Ohio, Michigan, and thence through Canada and Hudson's Bay to the north magnetic pole. A line supposed to be drawn through places of no declination is called the *agonic line.* At all places east of this line the needle points west of true north, and at all points west of it the needle points east of true north. The declination at New York in 1890 was 8.5° W., and at San Francisco it was 16.7° E. A line connecting all places where the declination is the same is called an *isogonic line.* But the declination at a given place changes from time to time. Thus at New York it will be 9.1° in 1900.

d. The angle made by the axis of a dipping needle with a horizontal plane is called the *dip* or *inclination* of the needle. At the magnetic pole the inclination would be 90°; the needle would stand upright. At the magnetic equator of the earth the inclination is 0°; the needle lies horizontal.

211. **The Meridians.** — *a.* The *geographical meridian* of any place is a vertical plane which passes through that place and the geographical North and South Poles of the earth. The *magnetic meridian* of any place in the northern hemisphere is a vertical plane passing through that place and the magnetic north pole of the earth (§ 210, *b*). The *direction* of the geographical meridian is that of a line drawn through the place toward the geographical North Pole. The *direction* of the magnetic meridian is that of a horizontal magnetic needle

when it is at rest, and free from all magnetic forces but those of the earth. The angle between these two meridians is the *declination* of the needle.

b. The measurement of declination is one of the three objects of magnetic surveys which are made by the government, the other two being the measurement of the inclination and of the magnetic intensity of the earth at various places. Exact results can be obtained only by means of instruments of precision used in the most skillful manner. But the following experiments afford a useful study of declination, and may yield very good approximate results.

Experiment 151. — *Object.* To mark the position of the geographical meridian on a table by means of a shadow at noon.

The table should stand in front of a window in the south side of the room. Support a slender rod, about a foot in length, upon the table in a *vertical* position. Before noon, when the sun is shining, carefully mark the middle of the tip of the shadow on the table by sticking in a pin. Mark it again and again, at short intervals, until after noon. The shadow will gradually shorten until noon, and then gradually lengthen. Through the point where the shadow was shortest, draw a line through the middle point of the foot of the rod; this line lies in the geographical meridian.

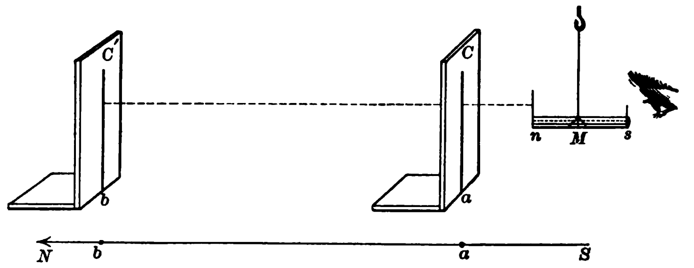

Fig. 285.

Experiment 152. — *Object.* To mark the position of the magnetic meridian on the table.

The apparatus is represented in Fig. 285. *M* is a bar magnet, with a fine sewing needle fixed upright at the middle point of each end by a bit of wax. It is suspended by a slender thread and nicely balanced, so that its length and breadth are both horizontal. *C* is a vertical piece of thin

wood, or of cardboard tacked to a wooden base, with a vertical black line drawn upon it. Now *M* will lie with its axis in the magnetic meridian when at rest, *if there be no iron in the vicinity, no air currents to disturb it, and the torsion of the thread is slight.* Let these conditions be secured.

Place the eye so that the two upright needles are in the line of sight. Then place *C* — or let a friend place it for you — just behind, and move it until its black line is in line with the needles. Mark the foot of this line, *a*, upon the table. Move *C* back about 1 m. Again place the black line in the line of sight, and mark its foot, *b*, on the table. Finally draw a straight fine crayon line through *a* and *b*. This line lies in the magnetic meridian; it points toward the magnetic north pole of the earth.

Experiment 153. — *Object.* To find the declination of the needle.

1. Lay down the geographical meridian, as in Experiment 151. 2. Lay down the magnetic meridian on the same table by Experiment 152, placing the point of suspension of the magnet, *M*, exactly over the geographical meridian. 3. Prolong the magnetic meridian until it crosses the other, and then measure the angle at the intersection of the two meridians, with a protractor.

212. **Electro-magnets.** — *a.* It was shown by Experiment 142, that a bar of iron is magnetized by an electric current in a wire wrapped spirally around it, and that the magnetism of soft iron is temporary, while that of hard iron or steel is permanent. Certain descriptive terms must now be defined. A coil of wire with few or many turns is called a *helix,* and one whose length is many times its diameter is called a *solenoid.* A bar of soft iron in a helix or solenoid is called an *electro-magnet.*

Experiment 154. — *Object.* To illustrate the most important facts relating to electro-magnets.

The apparatus consists of a battery, *B* (Fig. 286); an electro-magnet, mounted on a stand, *E*, with the ends of its helix attached to the lower ends of the binding posts fixed in the base; and a magnetic needle, *M*. The battery should be stronger than a Daniell cell. A bichromate cell is better, and two or three are better yet.

1. To test the magnetizing action of the current: Test the *core,* as the soft iron bar, *NS*, of the electro-magnet is called, by contact with small nails, to learn whether it is at all magnetic (§ 202, *b*). Then close the circuit by fixing the battery wires in the binding posts, and test the core again with nails and other small masses of iron. Finally open the cir-

cuit, and the fall of the nails instantly declares that the core is a magnet only so long as the current is on.

2. To test the polarity of the core: Close the circuit and bring the needle, *M*, toward one end of the core; if the north pole of *M* is attracted and the south pole repelled, that end of the core must be a south pole. Again bring the needle in front of the other end of the core and note its polarity. If the core is a magnet, its two ends have opposite polarities.

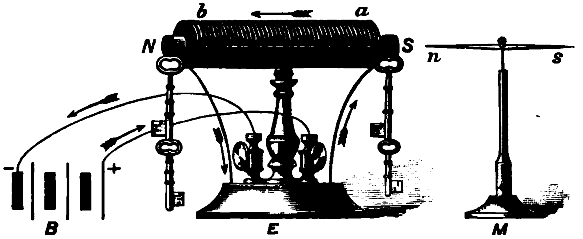

Fig. 286.

3. To discover whether the polarity of the core depends on the direction of the current in the helix: Trace the direction of the current (§ 187, *b*). In Fig. 286 it is shown to enter at *a* and to emerge at *b*. Test the ends of the core by means of the magnet, *M*, and note the polarity, N or S, of each. Then make the + and − terminals of the battery exchange binding posts, in order to reverse the current in the helix, or use a commutator (§ 187, *g*). According to the figure, it will then enter at *b* and emerge at *a*. Again test the polarity of the core. Repeat the experiments and write your conclusion.

b. The poles of an electro-magnet are reversed as often as the direction of the current in its helix is reversed. If the direction of the current in the helix is known, the polarity of the magnet is found by the following rule:

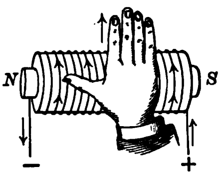

Fig. 287.

Place the palm of the right hand upon the helix, with the fingers pointing in the direction of the current in the windings (Fig. 287); *the outstretched thumb will point toward the north pole of the magnet.*

Conversely: The direction of a current in a helix may be found as follows: Test the electro-magnet with a needle to

find out which end of the electro-magnet is a north pole. Then place the right hand, palm down, upon the helix, with the thumb pointing toward the north pole; the fingers will point in the direction of the current in the windings. (Compare § 187, *b.*)

c. Helices are of two kinds, called *right-handed* and *left-handed.* If you face the end of a right-handed helix, you will see that the wire goes up on the left-hand side, and *down on the right-hand side,* while each successive winding of the wire is farther from the eye, like the threads of a screw when you look at the end (Fig. 288, I.). If you face the end of a left-handed helix, you will see that the wire goes up on the right-hand side and *down on the left-hand side,* while each winding of the wire is farther from the eye (Fig. 288, II.).

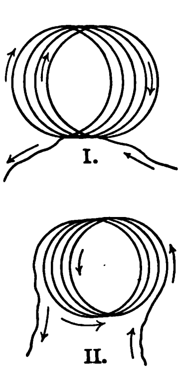

Fig. 288.

Evidently, if the current enters the corresponding ends of these helices, it will circulate in opposite directions, and produce opposite polarities in an electro-magnet. *The end of the core which faces you will be a south pole if the current enters a right-handed helix at that end,* but it will be a north pole if the current enters a left-handed helix at that end. This statement agrees with the hand rule given above (*c*).

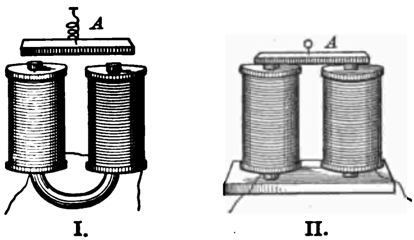

Fig. 289.

d. The most common form of the electro-magnet is that which is called the *horseshoe.* In this form the core is sometimes bent, as shown in Fig. 289, I., and sometimes it consists of two straight bars bolted to a

stout, soft iron crosspiece, called the *yoke*, as shown in Fig. 289, II. The coil of such a magnet is one wire wound in two parts, leaving the middle portion of the core, or the yoke, naked. The directions of the windings are such that if the core were straightened, the turns would be all one way in the two parts.

For most purposes the horseshoe is preferred, because its poles are near together, so that the field is more intense, and an armature, *A*, can be applied to both poles at once.

e. If an armature is not in contact with the poles (Fig. 289, I.), the electro-magnet, when excited by a current, attracts it, and will pull it into contact if it is free to move. When the armature is once in contact with the poles (Fig. 289, II.), it is held in place by an attraction many times greater than is exerted through even the thinnest air space. The attraction between an electro-magnet and its armature at a distance is called its *tractive power*; the attraction of the magnet and its armature when in contact with the poles is called its *lifting power*.

f. Electro-magnets may therefore be used for two purposes, — either to *produce motion* or to *resist pulls*, and they may be grouped in two classes, called, respectively, *attracting* or *tractive magnets*, and *holding* or *portative magnets*.

Fig. 290.

An example of tractive magnets is seen in the electric bell (Fig. 290). The terminals of the helix are fixed to two binding posts, *P*, *P*, on the frame. The armature, *A*, just in front of the poles, is pivoted at its lower end, while its upper end carries the hammer of the bell. A spiral spring, *S*, keeps the armature away from the poles, except when the circuit is closed. The core then becomes a magnet and pulls the armature, the spring

yields, and the hammer strikes the bell. On opening the circuit, the core is no longer a magnet, and the opposing spring pulls the armature away. In this class of magnets a current of high E.M.F. is desirable. How should the cells be arranged?

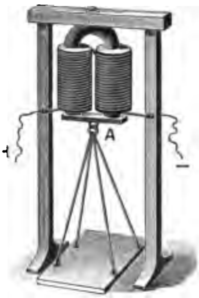

Fig. 291.

An example of portative magnets is represented in Fig. 291. The circuit is supposed to be closed. The armature, *A*, with its suspended platform, is upheld by the magnet in spite of gravity, and if additional masses are put upon the platform, their weight also will be supported, unless it exceeds the lifting power of the magnet. In this class of magnets the number of amperes of current is more important than volts. How should the cells be arranged?

213. **The Electric Telegraph.** — *a.* An electric telegraph is a set of instruments by which an electric current may be sent a long distance, and produce intelligible signals on its arrival at the distant station. In the Morse telegraph, which is the kind universally used in America, the vital part is an electro-magnet; the intelligible signals are produced by it, and all other parts are auxiliaries.

The essential parts of the telegraph are: 1. The *battery* (*B*, Fig. 292) or a *dynamo*, to generate a current; 2. The *line*, to conduct the current between stations; 3. The *key*, *K*, to open and close the circuit at the sending station; 4. The *receiver*, *R*, to convert the current into signals at the receiving station.

b. At the sending station a current from the battery, *B* (Fig. 292), is sent through the key, *K*, into the line wire, *LL*. By pressing the knob of *K* the circuit may be closed and opened at pleasure. At the receiving station the current goes through the coils of an electro-magnet, *E*, to earth, and thence back to battery. An armature, *a*, is held by a lever hinged

at *h*, and kept from contact with the magnet by an opposing spring, *s*. The lever carries a blunt point or a pen, *p*. Just below *p*, in the older instruments, is a roller turned by clock-

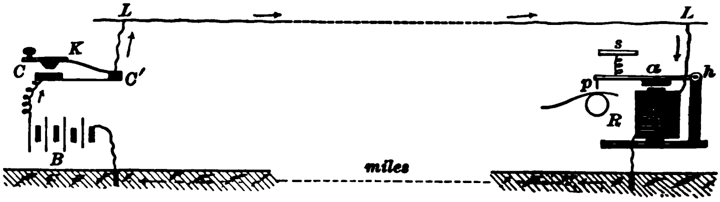

Fig. 292.

work, not shown in the figure, by which a strip of paper is carried along under the point. Now whenever the circuit is closed at *K*, the armature, *a*, will be attracted, and the point, *p*, will leave a mark on the paper below, but when the circuit is open the paper will pass untouched.

c. The marks on the paper consist of dots or dashes, made by closing *K* momentarily or for a longer time, and each letter of the alphabet is represented by some arrangement of these dots and dashes. For example, a dot followed by a dash (• —) stands for A, and a dash followed by a dot (— •) stands for N, while a dash followed by two dots (— • •) stands for D. The operator, by timing his pressure on the key, may cause the word *AND* in this form, • — — • — • •, to appear on the paper at the distant station.

A receiver which thus leaves on paper a record of the message sent is called a *register*. But in modern telegraphy the operator becomes acquainted with the clicks of the armature, and can recognize the letters by these sounds, so that the paper is not needed. Receivers from which messages are taken by sound are called *sounders*. Of course there must be a key and receiver at each station in order to send messages back and forth. Moreover the instruments on the line all click in unison with every message sent.

d. When the distance between stations is great, the current is not likely to be strong enough to give audible sounds. Hence an additional instrument called a *relay* is used. The relay is an electro-magnet wound with many turns of fine wire to make it sensitive to small currents. Its armature will respond to the feeble line current, and by its motion open and close the circuit of a local battery from which a strong current is sent through the receiver to produce the sounds or record the message. How this is done may be understood by means of the diagram (Fig. 293).

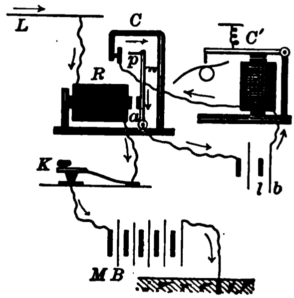

Fig. 293.

e. *R* represents the relay. The current from a distant station coming in at *L* may be traced by the arrows. It goes through the coil of the relay to the key, *K*, which must be kept closed while the message is being taken, thence through the main battery, *MB*, to earth. All that this feeble current has to do is to attract the light armature, *a*. Now the receiver, *E*, is in circuit with a separate battery, *lb*, known as a *local battery*, which is opened and closed at *p* by the armature, *a*. The course of this current may be traced by the arrows. All that this current has to do is to attract the armature of *E* with sufficient strength to produce the signals. Thus the relay's armature moves in obedience to the key at the sending station, and the receiver's armature responds to every motion of the relay. The diagram illustrates the instruments needed at each station, but a visit to the neighboring telegraph office is the best way to learn their actual appearance and many practical details which should not be here described.

214. **The Magnetic Field of a Current.** — *a.* The space surrounding a wire carrying a current is a magnetic field. This

is proved by the facts, first, that it magnetizes iron (§ 205, *a*), second, that it deflects magnetic needles. We are now to learn how the lines of force are distributed in this electro-magnetic field.

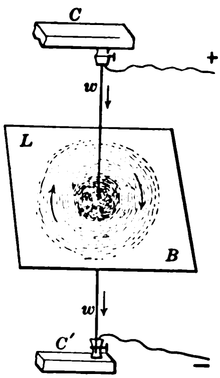

Fig. 294.

Experiment 155. — Support a sheet of stiff cardboard, *LB*, in horizontal position, and fix a stout copper wire, *ww*, vertically through its center (Fig. 294). Join the ends of this wire to the poles of a battery of many cells in multiple, so that a very strong current shall traverse the wire. Sift iron filings upon the cardboard, and, while gently tapping it, observe them creeping into circular concentric lines around the wire.

b. The arrangement of iron filings, shows that a sort of whirl — a magnetic whirl — pervades all the space around a wire in which there is an electric current. The lines of force are everywhere in concentric circles in planes perpendicular to the wire.

c. It is evident that if two wires lie side by side, their current fields will overlap, and the resultant field will not consist of concentric circles. In a helix, or solenoid, the windings lie side by side, and the current passes through them all in one direction. It is important to know the character of the resultant field.

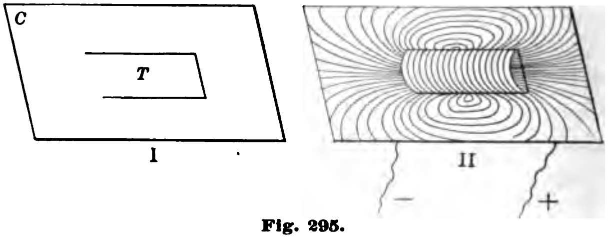

Fig. 295.

Experiment 156. — Measure the length and the diameter of a wide helix. Cut three sides of a rectangle in the middle of a sheet of cardboard, *C*, making a tongue, *T* (Fig. 295, I.), whose length is equal to that of the

helix and whose width is equal to the inside diameter. Bend the tongue and slip it through the helix and support the cardboard horizontally. Put the helix in circuit with a strong battery. Sift iron filings over the cardboard and, while gently tapping it, observe the lines of force as shown by the filings (Fig. 295, II.).

d. Two facts are revealed by Experiment 156: 1. The field outside the solenoid very closely resembles that of a bar magnet (Fig. 271). 2. The field inside the solenoid contains lines of force, nearly parallel, which appear to enter at one end and to emerge at the other.

e. Since the outside field of a solenoid carrying a current is so much like that of a bar magnet, we may suspect that *the solenoid is itself a magnet,* and further experiments prove that it is.

In Fig. 296 the ends of the wire of a solenoid are supposed to be soldered to a copper and a zinc plate, respectively. The solenoid is then suspended by a thread of raw, or untwisted, silk, with the plates in dilute sulphuric acid. A current generated by this zinc-copper cell must pass through the solenoid, entering at *a*. And now, if tested by a magnet, the end

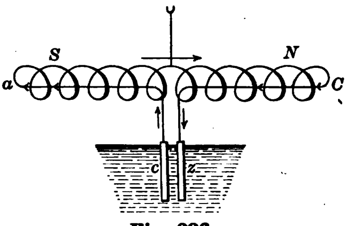

Fig. 296.

a will swing toward the north pole and away from the south pole, while the end *b* will behave in the opposite way. Moreover, the solenoid, when left to itself, will slowly swing into the magnetic meridian (§ 211, *a*) with the end *b* to the north. Thus a solenoid carrying a current is really a magnet, although it contains no magnetic substance.

XI. ELECTRO-MAGNETIC INDUCTION.

FUNDAMENTAL PRINCIPLES.

215. **Induction.** — *a.* We have seen (§ 177, *a*) that an insulated conductor in the field of a charged body is electrified. The action of a charged body on a conductor in its field is called *electrostatic induction.* We have seen (§ 205, *a*) that a magnetic substance in the field of a magnet is magnetized. The action of a magnet on a magnetic substance in its field is *magnetic induction.* It will be shown (Experiment 157) that a current is produced in a closed conductor, such as a coil of wire with ends joined, if the conductor is moved properly in a magnetic field. The action of a magnet or a current on a conductor moved in its field is called *electro-magnetic induction.*

Experiment 157. — *Object.* To illustrate the most important facts relating to electro-magnetic induction.

I. *By motion in the field of a magnet.* Adjust a sensitive galvanometer, *G* (Fig. 297), with its coils in the meridian, so that the needle when

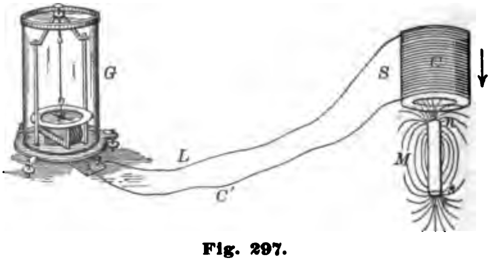

Fig. 297.

at rest points to zero of the scale. Connect *G* with a coil of copper wire, *SC*, by *long* wires, so long that *M*, which is a strong magnet, may be so far from *G* that it will not affect the needle.

1. When the needle of G is at rest, quickly carry SC down over the north pole to the middle of M and hold it there. The swing of the needle shows that a current is set up in SC by the motion. Note the direction of the swing. Does the needle settle to zero again? If so, then the current lasted only while SC was moving.

2. When the needle is at rest, quickly carry SC away from M. Does the needle swing — in the direction opposite to its former swing — and return to zero? If so, a current was set up in an opposite direction, while the motion of SC lasted.

3. Let the coil rest, and move the magnet, first into it, and then after observing the needle, out of it. If the same results as before are found, then it matters not which moves; it is the *relative motion* of coil and magnet that produces the current.

4. Repeat the experiments, using the south pole instead of the north pole of M. In each case the needle should swing in direction opposite that when the north pole was used.

II. *By motion in the field of a current.* The small coil, PC (Fig. 298), passes easily into the larger coil, SC. PC is joined to the terminals of a battery, and SC to the galvanometer, G (Fig. 297). Make the same experiments as in I. for the following purposes:

1. To learn whether a current is set up by the motion of SC to the middle of PC.

2. To learn whether another current is set up by motion of SC away from PC.

3. To learn whether PC instead of SC may be moved with the same results.

4. To learn whether changing the polarity of PC reverses the current in SC. For this purpose change the battery connections of PC.

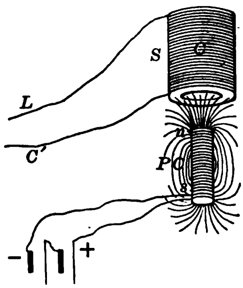

Fig. 298.

III. *By variations in the field itself.* Leave PC inside of SC, while you open, close, and reverse the current in PC by changing the terminals + and –, or better by a commutator (§ 187, g).

Or proceed according to Fig. 299. Place two coils, SC and PC, one upon the other. Send the battery current through a commutator, K, and the coil PC, while SC is joined to the galvanometer by long wires.

Begin with the circuit open and the needle at rest.

1. Close the circuit: *SC is suddenly filled with lines of force.* Observe the galvanometer to learn whether a current has been produced in SC.

2. Open the circuit: *SC is at once emptied of lines of force* by destroying the field. Observe the galvanometer to learn whether a current is produced in SC by withdrawing the lines of force from it.

3. Reverse the current: *SC is at once filled with lines of force directed the other way.* Observe the galvanometer to learn whether reversing the field also reverses the direction of the current in *SC*.

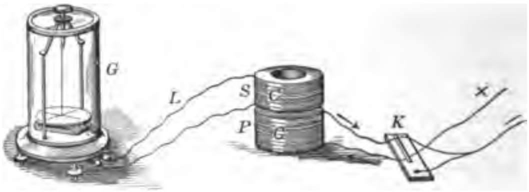

Fig. 299.

b. A coil through which a battery current passes is called a *primary coil.* A coil placed in the field of a primary coil is called a *secondary coil.* *PC* in the preceding figures designates primary coils, while *SC* designates secondary coils. A magnet, *M* (Fig. 297), is equivalent to a primary coil, because it produces the field which affects the adjacent coil, *SC*.

c. We know that the magnetic field is more and more intense as we approach the north pole of a magnet. Hence a coil, while approaching a north pole, must cut across lines of force at an increasing rate. So it must do also if it move toward the north pole of another coil, or if the field is thrown into it by closing the circuit of another coil. But in all these cases experiments prove that a current is induced in the coil *in the same direction.* This current is called an *inverse current,* because its direction is opposite to that of the primary, or battery, current which induces it. The law states that *increasing the number of + lines of force passing through a coil per second produces an inverse current.*

d. Experiments prove that when a coil approaches the south pole of a magnet, or of another coil, or when the field is taken out of it by opening the circuit of another coil, a current is induced in it *in the same direction.* This current is called a *direct current,* because its direction is the same as that of the

primary current which produces it. The law states that *increasing the number of — lines of force passing through a coil per second produces a direct current.* Increasing the number of — lines of force is the same thing as diminishing the number of + lines.

e. Experiments prove that whatever effect is produced by the motion of a coil from a weaker to a stronger part of the field, just the opposite effect is produced by the same motion from a stronger to a weaker part of the field.

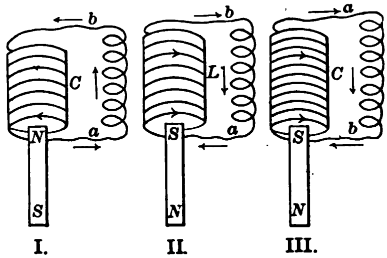

Fig. 300.

Thus if a right-handed helix (§ 212, *c*), as shown in Fig. 300, I., is moved down over the north pole of a magnet, with the end *a* ahead, an *inverse* current is induced, going *through the coil* from *b* to *a*. But let it go down over a south pole, with the same end ahead (Fig. 300, II.), and a *direct* current is induced, going *through the coil* from *a* to *b*.

f. This law does not forbid the production of a current in the same direction *through the wire* of the coil by a north and a south pole, because the coil itself may be reversed at the same time that the pole is changed. Thus, in Fig. 300, I., the coil goes over a north pole, with the end *a* ahead, and in III. it goes over a south pole, with the end *b* ahead. The current goes *through the wire* in the same direction, from *b* to *a*, in both cases.

g. Experiments show that the current induced by carrying a coil towards or away from a magnet is made stronger by moving the coil more rapidly. This is because the number of lines of force in the coil increases or diminishes more rapidly when the coil moves faster. The law states that *the*

E.M.F. induced is proportional to the RATE OF CHANGE *in the number of lines of force which the coil cuts.*

h. It is not the presence of the field that induces a current, but it is the *change in its strength.* So it is not the strength of field which determines the E.M.F. of the induced current, but it is the *rapidity with which the strength changes.* Careful study of Fig. 301 may help one to understand this important fact. A loop of wire, *c* (*A*), is seen edgewise in the uniform field (§ 206, *b*) *NS*, and is supposed to move in the direction of the arrow and to be kept parallel to itself all the time. Observe that there is *no change* in the number of lines it cuts across. Consequently no induced current is produced in

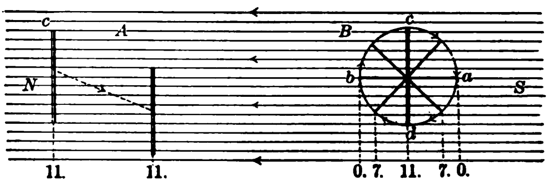

Fig. 301.

it. The loop may move in any other direction, and with any speed, without producing a current, provided it is kept parallel to itself, because the magnetic strength it encounters does not change. But let the loop revolve in the field, as at *B*. Starting from its vertical position *c*, it *cuts across* the lines more directly and hence more rapidly, until it reaches *a*, then less directly and rapidly until it reaches *d*, again more rapidly to *b*, and again less rapidly to *c*. This *variation* in the change of magnetic strength produces an induced current in the loop; and the *rapidity* of the variation, which keeps pace with the speed of the rotation, determines the E.M.F. of the current.

i. Induced currents are greatly intensified when soft iron cores are placed in the primary coils. The cores become mag-

nets, and increase the strength of the field by adding largely to the lines of force therein.

216. **Self-induction.** — *a.* A current when interrupted by opening and closing the circuit, induces an E.M.F. in its own wire as well as in others which lie in its field. The action by which a current induces an E.M.F. in its own wire is called *self-induction* or *inductance.* Consider the following experiment:

Experiment 158. — *Object.* To verify the production of currents by self-induction.

In Fig. 302, C represents a coil of wire with a soft iron core; C', a cell with its $-$ pole connected with one end of the coil and its $+$ pole with a key, K, and this to the other end of the coil; G, a galvanoscope connected to the coil wires at L and M. Close this circuit by pressing the knob K. The current divides at L, part going through C, and a part through G, from L to M, deflecting the needle. Push the needle back to zero, and put a block against it to keep it from going again the same way, while leaving it free to move the other way. Now open the circuit at K, and observe that the needle does swing the other way. This shows a current from M to L; it could not come from C' because the circuit was open; it must have come from C, and its direction must have been that shown by the arrows — the same as that of the battery current itself.

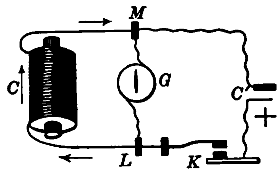

Fig. 302.

b. The facts are that when a current is started an inverse E.M.F. is set up, and when the current is stopped a direct E.M.F. is set up in the same wire. Of course the effect of the first, or inverse, E.M.F. must be to delay or weaken the primary current, while the effect of the direct E.M.F. is to prolong or strengthen the primary current.

c. The reason that there is an inverse E.M.F. on closing the circuit may be found in the mutual action of the current and the medium which it invades. The current has to produce a magnetic field; that is, it must produce strains in the medium around it.[1] To do this is work. This work absorbs a part

[1] The "lines of force" are the directions of these strains.

of the electric energy of the current, and takes an appreciable time to do it. During the time taken to establish the field there is, therefore, a back pressure, or counter E.M.F., from the field. This counter E.M.F. opposes, and hence delays and weakens, the primary current.

But when the circuit is opened, the primary current ceases. Then the elastic medium, recovering from its strains, pours its electric energy back upon the wire, and thus produces an E.M.F. in the same direction as that of the battery. This direct E.M.F. is not opposed by any current, but by the resistance of the circuit only, and will produce a current if that resistance is not infinitely great.

d. The current of self-induction produced by breaking the primary is called the *extra current.* If the primary circuit consists of a single turn of wire, there will be little inductance, but if it be a helix of many turns there will be much, and still more if the wire is coiled around an iron core. In this case the E.M.F. of the extra current is remarkable. It will cause a brilliant spark on breaking circuit, or give a "shock" to a person holding the two ends of the coil when the circuit is opened.

e. Self-induction occurs only while the primary current is changing. The law states that *an inverse E.M.F. is produced whenever the number of lines of force in a coil is increasing, and a direct E.M.F. whenever the number of lines of force in the coil is decreasing.*

Whether this E.M.F. is inverse or direct, it tends to counteract the primary current. Thus it prevents a battery current from reaching full strength as quickly as it otherwise would on making circuit; and it prevents the current from dying out as rapidly as it would when the circuit is broken. It is opposed to *any change* in the primary. Hence inductance is equivalent to a resistance (§ 194, *a*). A steady current is opposed by the resistance of the wire only, but an unsteady

current is opposed by the resistance of the wire, and also by self-induction. The sum total of resistances due to both these causes is called *impedance.*

The inductance in a coil is a serious difficulty when we require either rapidly alternating currents or a rapid succession of momentary currents by opening and closing circuit.

THE DYNAMO MACHINE.

The electric currents used on the largest scale, to produce light, to drive machinery, to deposit metals, and for many other purposes, are generated by induction. The machines employed are known as *dynamos.*

217. **The Dynamo.** — *a.* A dynamo is a machine to convert mechanical energy into electric current by revolving closed coils in the field of an electro-magnet.[1] There are two classes, one known as *continuous-current dynamos,* which furnish currents continuously in one direction, and the other as *alternating dynamos* or *alternators,* which furnish a rapid succession of currents alternately in opposite directions.

b. Let us first study a simple case, to see how a continuous current may be maintained by the motion of a coil in a magnetic field.

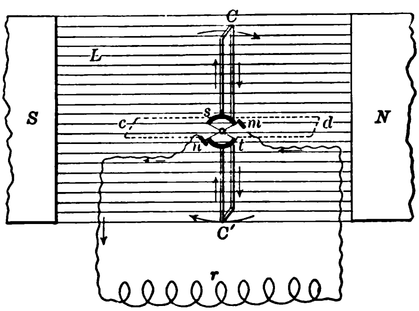

Fig. 303.

In Fig. 303, CC' represents a loop of wire, which may be revolved in a magnetic field, L. The loop terminates at one end in a semicircle of copper, s, and at the other end in another

[1] A permanent magnet is sometimes used in small machines; in this case the machine is called a *magneto-electric machine,* or simply a *magneto.*

semicircle, *t*. There is a spring, *m*, which presses against *s*, and *n* is another which presses against *t*. These springs are connected by a wire, *r*. When the loop revolves, *s* and *t* will slide around under *m* and *n*. So long as *m* and *n* touch the semicircles, the circuit of the loop is complete through *mrn*, but when the open spaces come around to them, the circuit will be broken. This will happen whenever *CC'* is vertical, or twice in every revolution.

The loop revolves in the direction of the arrows, and we will suppose that it has just passed the vertical so that *m* is upon *s* and *n* upon *t*. While the loop goes from *C* over to *d*, it cuts across the lines of force *more rapidly*, and an inverse current is set up in it from *s* to *t*. During the next quarter revolution, it cuts across the lines of force *less rapidly*, but they *pierce the loop from the other side*, and hence the current is in the same direction as before, from *s* to *t* (§ 215, *f*). Thus during this half revolution the current *in the loop* is from *s* to *t*. During the other half revolution it will be the other way, from *t* to *s*.

The current *in the loop* is reversed every time the loop passes the vertical position, twice in every revolution. But it is not so *in the wire r*. In the first half revolution, *t* is in contact with *n*, so that the current in the loop from *s* to *t*, completes its circuit through the wire from *n* to *m*. In the second half revolution *s* is in contact with *n*, so that the current in the loop from *t* to *s*, completes its circuit through the wire from *n* to *m*, the same direction as before. Thus while the current *in the loop* is alternating, it is continuous *in the wire outside*.

c. In order to produce and maintain a strong continuous current, the essential parts of a dynamo are:

1. Powerful electro-magnets, *S*, *N* (Fig. 303), to establish an intense field. These are called *field magnets*.

2. Coils with many loops inclosing a soft iron core (in place of *CC'*, Fig. 303) to be revolved in the field by mechanical power. These together are called the *armature*.

3. A device by which to change the alternate currents of the armature into a continuous current (represented by *st*, Fig. 303). This is called the *commutator.* It usually consists of insulated bars of metal, fixed upon the axle or shaft to which the mechanical power is applied.

4. Metal springs in contact with the commutator to lead the current off into the outside circuit (in place of *m* and *n*, Fig. 303). These are called the *brushes.*

d. The field magnets are excited by current taken from the armature which revolves between their poles. There is always enough residual magnetism left in the cores to start the current, and once started the current strengthens the magnets; they in turn intensify the field and increase the current.

Sometimes the *whole* of the current from the armature is carried around the cores, and thence through the outside circuit, and sometimes only *a part.* If the entire current goes around the cores, the machine is called a *series dynamo;* if only a part, the machine is called a *shunt dynamo.*

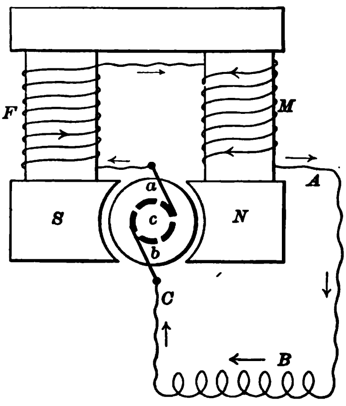

Fig. 304.

Fig. 304 illustrates the winding of a series dynamo. Between the massive pole pieces, *N*, *S*, of the field magnet *FM*, the armature with its commutator, *c*, revolves. The current, taken off by the brush, *a*, goes first round the cores and then out through the main circuit, *ABC*, back to the other brush, *b*, lighting lamps or doing other work on its way.

Fig. 305 illustrates the winding of a shunt dynamo. At *a*, the current divides; a part takes the wire around *FM* and

goes directly back to *b*, while the other part takes the main circuit, *ABC*, on its way back to *b*.

Sometimes two coils are wound upon the magnets, one in series with the line outside, the other in shunt. This combination of series and shunt is called *compound winding*. One or another of these methods is adopted according to the kind of work to be done by the current, as we shall see.

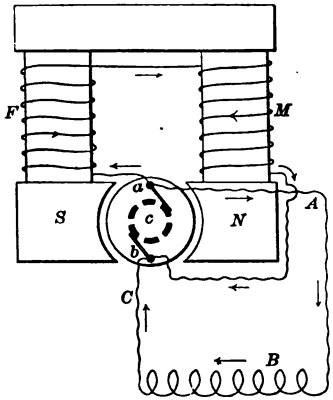

Fig. 305.

e. The armature coils are sometimes wound upon a soft iron ring and sometimes endwise around a soft iron cylinder. The latter is the most common winding. When the coils encircle a ring, the armature is called a *ring* or *Gramme armature;* when they lie lengthwise on the outside of a cylinder, the armature is called a *drum* or *Siemens armature.* Other forms of armature may be found described in larger works on physics.

Fig. 306 illustrates the construction of a Gramme armature. The ring of soft iron, *kk*, is completely covered with separate coils, of which only eight are shown. It is fixed upon a horizontal shaft on which are insulated bars of copper whose ends are shown by the heavy short lines; these form the commutator. The coils are all connected in series by the commu-

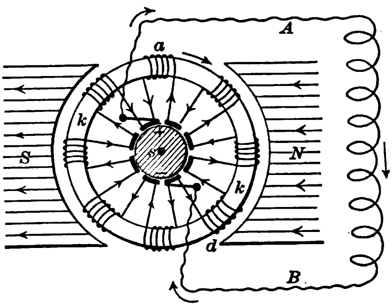

Fig. 306.

tator bars, — each bar connecting the adjacent ends of two adjacent coils, as shown. The shaft *s*, carrying the ring and commutator, is supposed to be driven rapidly by a steam engine, or other "power," through the intense field of the pole pieces, *N*, *S*, in the direction of the arrow, *a*. The action of this armature can be readily understood from § 217, *b*.

f. The cores of armatures are not made of solid rings or cylinders, but consist of a bundle of insulated wires, or, better, of thin sheets of metal. This is to avoid what are called *eddy currents* — currents which are always set up in the iron around which a current circulates. These eddy currents produce heat in the iron and reduce the efficiency of the machine. They are largely prevented by making the core of bundles of thin sheets insulated from one another.

g. When a current of high E.M.F. is desired, as for lighting arc lamps in series, the coils of the armature are joined *in series* as described (*d*); but when a current of low E.M.F. is wanted, as for lighting incandescent lamps in multiple, the coils of the armature are joined *in multiple*.

The E.M.F. is *proportional* to the number of loops of the armature coils in series. It is also proportional to the strength of the field magnets, and also to the speed with which the armature revolves. It is therefore easy to see that the same machine is not adapted to all purposes, and, in a general way, how the construction must differ for different kinds of work.

218. **Alternate-current Dynamos.** — *a*. The most essential difference between an alternator and a continuous current dynamo is this: The alternator has no commutator, so that the induced currents are taken from the armature just as they are generated — in alternate directions. Instead of a commutator there are insulated metallic

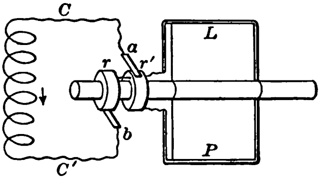

Fig. 307.

rings, r, r' (Fig. 307), on the shaft, to each of which one end of the coil is joined. The brushes, a and b, press upon these rings, and as the armature, represented by the loop LP, revolves, the inverse and direct currents are set up alternately through the circuit consisting of the loop, the rings, the brushes, and the outside conductor, CC'.

b. Every change in direction is called an *alternation.* Thus if a machine is said to produce 266 alternations per second, it reverses its current 266 times per second, or it produces 133 currents in one direction and 133 in the opposite direction. In this case there would be 133 complete to-and-fro motions of the current, and this number of complete to-and-fro motions, or one half the number of alternations per second, is called the *frequency* of the current. The frequency for ordinary purposes of electric lighting and transmission of power varies between 100 and 200 per second.

c. The frequency of an alternating current depends on the number of pole pieces of the field magnets and the speed of the armature. Thus a single field magnet with its two pole pieces will give two alternations for each revolution of the armature. Let there be four field magnets with their 8 pole pieces surrounding an armature which is driven at the rate of 10 revolutions per second, and there would be 80 alternations per second, and the frequency would be 40.

Frequency $= \frac{1}{2}$ (No. of pole pieces $\times$ No. of revolutions per second).

Example. — In order to secure "high" frequency, let us have a dynamo with 200 poles arranged alternately, N and S, and drive the armature at the rate of 120 revolutions per second. Compute the frequency.

d. But another method of obtaining high frequency currents has been devised by Nicola Tesla. In the Tesla alternator, the armature coils are fixed to a piston rod and driven, like the piston of a steam engine, back and forth, in the field of a powerful electro-magnet; they do not *rotate* but *vibrate* in the field.

e. The E.M.F. of an alternating dynamo is the *average* difference of potential it maintains. The maximum will be double the average. Hence the greater penetrating and shock-giving power of the alternate current than of a continuous current of the same voltage.

f. The field magnets of all dynamos require continuous currents to excite them; hence alternators cannot use their own currents, but a separate small continuous-current dynamo is generally employed for this purpose.

ELECTRIC MOTORS.

219. Electric power has recently been substituted for steam power for many industrial purposes, such as running elevators, propelling railway cars, and driving machinery in manufactories. Electric power is developed by the electric motor.

220. **The Electric Motor.** — *a.* An electric motor is a machine for converting electric currents into mechanical energy. Its action may be explained as follows:

We have seen that the lines of force in the field of a current are directed in concentric circles (§ 214, *b*). What would happen if two wires carrying currents should lie side by side so that their fields would overlap? Experiments prove that parallel conductors carrying currents in the same direction are pulled together, but if the currents are in opposite directions they are pushed apart.

If the currents are in the same direction, their lines of force, in the overlapping parts of their fields, are in opposite directions. This will be readily seen by imagining two wires instead of one to pass through the card, *LB* (Fig. 294), and the lines encircling both in the same direction. Hence the principle of attraction and repulsion may be stated for lines of force as follows: *If the lines of force in two overlapping fields are in the same direction they repel, and their wires are*

pushed apart, if in opposite directions they attract and their wires are pulled together.

Now suppose a wire carrying a current to lie across the uniform field between the poles of a horseshoe magnet. The case is represented by Fig. 308.[1] The wire carries the current in the direction of the arrow *A*. It will be seen that the lines of force in the field, above the wire, are in the same direction, but in opposite directions below it. Above the wire they repel each other and *push* the wire down. Below the wire they attract each other and *pull* the wire down. This is

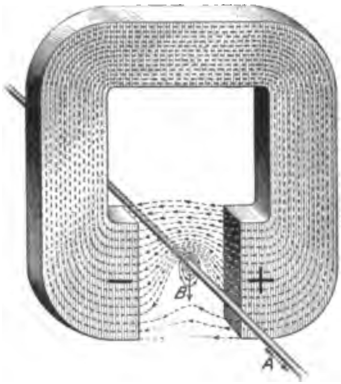

Fig. 308.

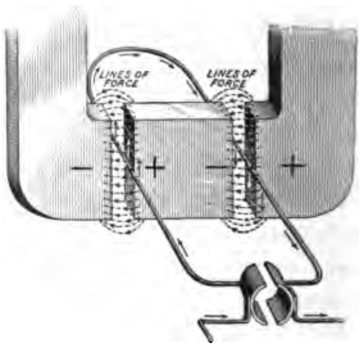

Fig. 309.

just what happens: *A movable wire is pulled through the field of a magnet, if it carry a current across the field between the poles.* Let the current be reversed and the wire will be pulled through the field the other way.

Next suppose the current to go around a loop of wire at right angles to the lines in the field of the magnet, as shown by Fig. 309. Since the current in the two branches crosses the field in opposite directions, one branch will be pulled up-

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[1] *The Electric Motor, an Address before the New England Railroad Club.* By James F. McElroy.

ward, while the other will be pulled downward, as shown by the arrows, causing a rotation of the loop. A block of iron within the loop, as shown, strengthens the magnetic field so that the loop is driven with greater energy.

When many loops are wound around an iron core, so pivoted as to permit rotation in the field of a powerful magnet, and a strong current is sent through the coil, the energy of rotation is enough to drive machinery.

b. A motor contains the same essential parts as a dynamo (§ 217, *b*). In fact, a continuous-current dynamo may be used as a motor by applying a current, instead of mechanical power, to drive its armature. As a dynamo, the machine receives mechanical energy at its pulley to drive the armature in the magnetic field and produce a current. As a motor, the same machine receives a current into its armature, which is then driven the other way round by the field, producing mechanical energy, which it delivers from its pulley. In principle a motor is a dynamo reversed.

c. Except for the inevitable waste in transferring energy, the power which a motor can deliver is equal to the power used to generate the current which drives it. Thus suppose a 10-horse-power engine to drive a dynamo, and that the dynamo current is used to drive a motor; if there were no waste of energy in the machines, the motor would deliver 10 horse-power to drive machinery in a workshop. But practically a large fraction of the 10 horse-power is wasted (§ 24, *c*). Friction and electrical resistance in the dynamo will use up, say, 10 per cent, so that the *output*, as that which it delivers is called, will be only 9 horse-power, or a current of $746 \times 9 = 6714$ watts. Then the motor, by its friction and electrical resistance, will use up perhaps 20 per cent of the current it receives, so that the output of the motor will be only 80 per cent of 6714, or about 5371 watts, or a little more than $\frac{7}{10}$ of the power used to drive the dynamo. The

efficiency (§ 30) is still less, if the current is carried far, on account of resistance and leakage along the conductor.

d. Since so much of the original power is wasted in the dynamo and motor, it would seem to be more economical to use the steam engine directly. But there are advantages in the electric power which offset the losses. 1. Steam power and water power must be used on the spot where they are generated, while electric power may be conveyed by wires and used in manufactories long distances away. A central plant may send power to many shops, and the cheap water power of a stream may be utilized in a city miles away. Thus a mite of the vast energy of Niagara is being converted into kilowatts[1] and sent out to do work in Buffalo, and it is not impossible that some time in the future it will be sent to Albany and New York. 2. The electric motor is more reliable, less cumbersome, more cleanly, and requires less attention and repair than a steam engine.

e. Electric motors placed on cars will propel them singly or in trains if sufficient current be supplied. Thousands of miles

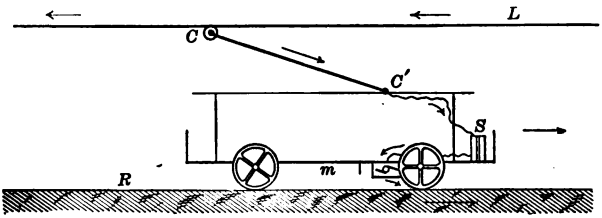

Fig. 310.

of electric railways exist in the United States alone. There are several ways to supply current to the motors, but the "overhead trolley system" prevails in this country. The ideal diagram (Fig. 310) illustrates the method employed.

From a powerful dynamo located in the "power house," the

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[1] The prefix *kilo* everywhere means 1000.

current is led off by the "trolley wire," which is supported by poles erected along the highway to be traversed. From this wire, *L*, current is taken by the trolley, *C*, — a metal wheel which rolls against it. The current passes along the trolley pole hinged upon the car at *C'*, and thence to a switch, *S*, by which the motorman controls its strength and direction. From the switch the current goes to the motor, *m*, located under the car floor and attached to the axle of the wheels. The current having driven the motor which propels the wheels, is carried by the wheels to the rails, *R*, and the earth, which form the return circuit to the dynamo.

TRANSFORMERS.

221. **Transformers.** — *a.* A *transformer* is an instrument which changes the E.M.F. and strength of a current by induction. Such changes are required in order to adapt a given current to the work which it is to do. For example: If a current is to be sent through a great resistance, as that of many miles of wire, its E.M.F. should be high, while its strength is of less account; but if the current is to do work after it reaches a distant station, its E.M.F. may be lower, while its strength is more important.

b. The essential parts of a transformer are two coils, with a difference in the number of windings and size of wire, wound on the same soft iron core.

Faraday, who first discovered the principle of induction, used two forms of apparatus which may be studied as the types of all modern transformers. One of these is known as *Faraday's ring;* the other may be called *Faraday's concentric coils.*

c. Faraday's ring is shown in Fig. 311. A ring of soft iron, *R*, carries two insulated coils, *A* and *B*, wound on separate parts of it. If coil *A* is connected with a battery or

dynamo, induced currents are set up in B whenever the current in A is turned on or off. When the current is turned on, R is magnetized and its lines of force are sent through B, and when the current is turned off, the lines of force are withdrawn. B is thus alternately filled with lines of force and emptied, and this alternate increase and diminution of the force produces currents (§ 215, *d*, *h*).

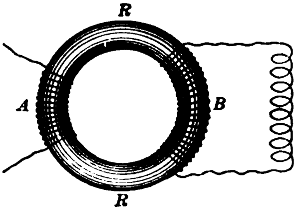

Fig. 311.

Now the E.M.F. is found to be higher in the coil having the larger number of windings. Accordingly if we would raise the E.M.F. of a current, we should send it through the coil of least number of turns and take the induced current from the other; but if we would lower the E.M.F., we should send the primary current through the coil of larger number of turns and take the induced current from the other.

d. Faraday's concentric coils are shown in Fig. 312. A bar of soft iron, L, carries two insulated coils, C and C', one wound outside the other. Either coil may be the primary; the other will be the secondary (§ 215, *b*). Induced currents will be set up in the secondary as often as the primary circuit is opened and closed. If the secondary coil has the greater number of turns, the E.M.F. will be increased; but if it has the lesser number of turns, the E.M.F. will be diminished.

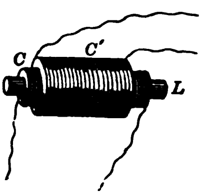

Fig. 312.

e. In fact: *The E.M.F. of the induced current is to that of the primary current as the number of turns in the secondary coil is to the number of turns in the primary.* For example: Suppose one coil has 20 turns and the other 1000, then if the given current is sent through the 20-turns coil, the induced current should

have an E.M.F. 50 times as great (1000 ÷ 20). Or if the given current is sent through the 1000-turns coil, the induced current should have an E.M.F. $\frac{1}{50}$ as great (20 ÷ 1000).

Suppose we have a battery current of 10 volts and desire a current of 1000 volts; what must be the ratio of the turns in the coils of the transformer?

Practically, the above law is not strictly true because there is always some waste of energy in the transformer.

f. It is evident (§ 215, *h*) that no transformation occurs so long as the primary current is continuous. The current from a battery or a continuous-current dynamo must be weakened and strengthened rapidly in some way. The most usual way is to open and close the circuit by a device called a *contact breaker.* Thus, in Fig. 313, *CC′* represents a transformer with a contact breaker, *hp.* A disk of soft iron, *h*, is supported by a spring in front of one end of the core and in contact with a metallic point, *p.* One terminal, *A*, of the primary coil is in connection with *h.* The battery is in connection with the other terminal and also with the point *p.* The action is as follows: The current magnetizes the core, and the core attracts *h* away from *p*, opening the circuit. The core is no longer a magnet; *h* springs back to *p*, closes the circuit, and magnetizes the core. Thus the current is rapidly sent into and out of *C*, and induced currents in *C′* follow with equal rapidity. Transformers for alternate currents need no contact breaker.

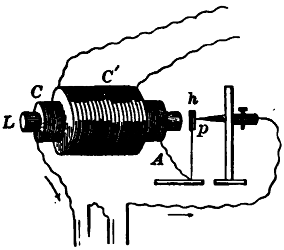

Fig. 313.

g. Transformers are needed when glowlamps are to be lighted, or machinery is to be driven by currents at places far away from the generators. For example: Glowlamps require strong currents of many amperes, and from 50 to 100 volts E.M.F. But such currents require larger and more costly

copper wires to convey them than if they had little strength, and very high E.M.F. by which to overcome the resistance of smaller ones (§ 194, *c*, 2). Thus cheaper conductors and less loss of E.M.F. are secured. Hence the plan adopted is to generate the current at a pressure (§ 193, *a*) of 1000 to 5000 or more volts, and then transform it down at the distant station, to the necessary 50 or 100 volts to light the lamps.

Alternating dynamos chiefly are employed to produce the high pressure currents (§ 218, *e*), and the transformer which is used is called a *step-down transformer* because it lowers the E.M.F. Its primary is a coil of many turns of small wire, and its secondary is a coil of few turns of coarse wire.

h. In transforming currents there is no gain or loss of energy; the law of conservation (§ 18, *b*) is as exacting here as elsewhere.

Thus the *power* of a current,—that is, the rate at which it can do work,—is found by multiplying its strength by its E.M.F.

$$\text{Power} = \text{amperes} \times \text{volts, or } W = I \times E.$$

Now the product (amperes × volts) is constant; if the volts are increased by the transformer, the amperes are diminished in the same ratio, and if the volts are diminished the amperes are increased accordingly.

Thus: If a transformer whose primary coil has 30 times as many turns as its secondary, receives a current of 5 amperes at 3000 volts, it should deliver a current at 3000 ÷ 30, or 100, volts, and 5 × 30, or 150, amperes.

Examples.—1. To transform down from 2000 volts to 50 volts, what must be the ratio of the windings in the transformer? Which will be the primary coil? If the 2000-volt current has strength of 5 amperes, what will be the strength of the 50-volt current obtained?

2. To transform up from a current of 40 amperes at 10 volts, to one of 1000 volts, what must be the ratio of the windings? Which coil must receive the 10-volt current? What will be the strength of the 1000-volt current?

i. The power of a current is measured in units called *watts.* A watt is the power of a current of 1 ampere at 1 volt. 746 watts are equal to 1 horse-power (§ 16, *b*).

$$\text{Watts} = \text{amperes} \times \text{volts} = \text{horse-power} \div 746.$$

Thus a current of 1 ampere at 1000 volts would have a power of 1000 watts, and be able to do work at the same rate as steam in a steam engine of 1000 ÷ 746, or about 1.3, horse-power.

But the current of 1 ampere at 1000 volts would not be adapted to all kinds of work. It would not, for example, successfully light ordinary incandescent lamps for which a current of 100 volts is required. Now a step-down transformer will change this 1000-volt current to one of 10 amperes at 100 volts, the power remaining the same, 1000 watts. Some leakage or loss is inevitable in every transfer of energy, but aside from this a transformer does not change the *power* of a current.

j. Again, lamps are often described by stating the power required to light them. Thus an arc lamp which takes 10 amperes at 50 volts, or 500 watts, is said to be a 500-watt lamp. Two such lamps, joined in series, would take the 1000 watts of current, which, as in the above illustration, should be furnished by a dynamo driven by a steam engine of about 1.3 horse-power. In practice a much more powerful engine is needed, on account of the wasted work which is inevitable (§ 24, *c*).

Example. — If no losses occur in transferring the energy, how many 450-watt arc lamps at 45 volts can be lighted, in series, by the current from a dynamo driven by a steam engine of 50 horse-power? What would be the strength of the current?

222. **Induction Coils.** — *a.* Step-up transformers, intended to deliver currents of such high E.M.F. as to produce spark discharges through air, and other effects like those of static

electricity, are called *induction coils.* They are constructed on the type of Faraday's concentric coils (§ 221, *d*). The primary coil consists of a *few turns of large wire,* so that it may carry large currents of low E.M.F. with little loss from resistance. The secondary coil consists of a *very great number of turns of small wire,* so that the ratio of windings may be as large as practicable (§ 221, *e*) without making the coil too cumbersome. The central core is of the softest iron, so that it will be promptly magnetized and demagnetized by momentary currents (§ 212, *a*), and it is preferably made up of small wires, so that less heating by eddy or Foucault currents (§ 218, *f*) will occur.

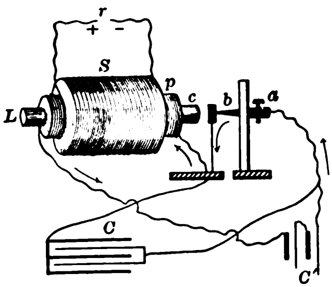

Fig. 314.

b. Besides these vital parts, the instrument is provided with a contact breaker, so that the continuous current of a battery shall become intermittent, and a condenser (§ 180, *a*), so that the extra current (§ 216, *d*) shall be drawn off and not permitted to prolong the primary current when the circuit is opened.

The relation of all these parts to one another is shown in Fig. 314, and one actual form of the instrument in Fig. 315. The course of the primary current may be traced by the arrows. The secondary current will break across an air space, *r*, between the ends of the secondary coil + and −, as a spark.

Fig. 315.

c. The condenser and its action needs some further explanation. It is practically a large Leyden jar (§ 180, *a, b*). It

consists of two sheets of tin foil separated by paraffined paper. In order to have large surfaces in compact form, the two tin-foil sheets are folded, and their folds alternate as shown at C (Fig. 314). One sheet is joined to the primary circuit on one side of the contact breaker; the other sheet is joined to the primary circuit also, but on the other side, so that the circuit through the condenser is opened and closed at the same instant as the primary.

On closing circuit, the self-induced current in the primary coil will not be affected by the condenser, and it will, as explained in § 216, *e*, compel the primary current to *take some time to reach full strength.* But on opening the circuit, the extra current will take to the condenser and be spent in charging it instead of opposing the primary current, so that the primary current should *cease instantly.* Thus the secondary coil is filled *gradually* with lines of force on closing, but emptied *instantaneously* on opening, the circuit. Hence the inverse current is feebler than the direct. In fact, it is only the direct current which has high enough E.M.F. to leap the air space and produce the sparks.

THE TELEPHONE.

223. **Telephony.** — *a.* Telephony is any process by which an electric current causes sounds which are made at one place to be repeated at another. It is sometimes defined as the art of transmitting sound by electricity, but this definition is faulty because no sound, but an electric current only, passes between the distant stations. The fact is, that the energy of sound waves produces an electric current at one station, which, on reaching the distant station, reproduces similar sound waves there. The combination of instruments by which this is done is called a *telephone.*

b. The essential parts of a telephone are three: The *trans-*

mitter, by which sound waves generate or modify an electric current; the *line*, by which the current is transmitted to the distant station; the *receiver*, by which the current reproduces sound waves. In the original Bell system, the transmitter and receiver were identical in form, but in the modern system the two are quite different. The Bell telephone depended entirely on induction; in the modern system, the transmitter employs a battery current, and only the receiver operates by induction.

224. **The Bell Telephone.** — *a.* Fig. 316 represents the Bell instrument, in perspective and in section. *B* is a steel magnet, with one end encircled by a coil, *C*, of many turns of fine wire, the ends of which are in the binding posts, *P*, *P*. *D* is a thin disk of sheet iron in front of the magnet, and *E* is a funnel-shaped cavity for the lips when the instrument is used as a transmitter, and for the ear when it is used as a receiver.

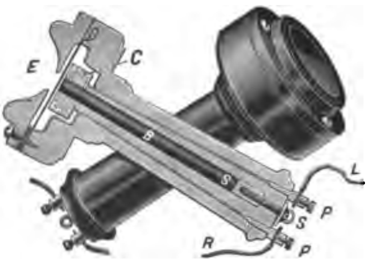

Fig. 316.

The diagram (Fig. 317) shows the connection of two stations, *L* and *M*. *CC′* is a wire reaching from one to the other, with each end joined to one terminal of the Bell instrument, while the other terminal is joined to earth.

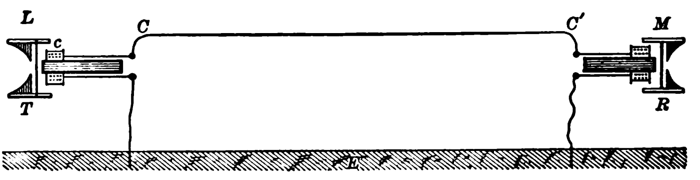

Fig. 317.

b. When one speaks into either of these instruments, say *T*, the disk is made to vibrate in unison with the air waves of the

voice. As it swings toward the pole of the magnet, the field is strengthened, and a current is set up in the coil, *c*. When it swings back, the field is weakened, and a current in the coil is set up in the opposite direction. These induced currents go over the line and through the coil of the receiver, *R*, at the distant station. There they alternately increase and diminish the strength of the field of the magnet. When the field is stronger, the disk is pulled more strongly toward the magnet; when it is weaker, the disk is less attracted and springs back. Thus *the motions of the disk T are repeated by the disk R.* But the vibrating disk, *R*, produces air waves, and similar air waves are recognized as similar sounds. Hence the sound at *T* will be repeated to an ear at *R*.

225. **The Carbon Transmitter.** — *a*. In the modern transmitter, a battery current is made to pass through carbon so arranged that *its resistance is changed by varying the pressure upon it.* We know that a current is weakened by passing from one conductor to another when they are loosely joined, because of the large resistance due to loose contact. By pressing the conductors more closely together, the current is strengthened. In carbon transmitters, the pressure is varied by the air waves of the voice, and a steady current is thus changed into one which is undulatory.

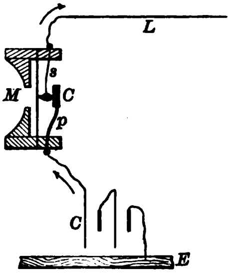

Fig. 318.

b. The instrument in common use is known as the *Blake transmitter*. Its action may be understood by means of the diagram (Fig. 318). Behind the disk is a slender spring, *s*, with a little platinum knob on the end, which is held with slight pressure against the middle of the disk. Another spring, *p*, causes a carbon button to press lightly against the platinum knob. One terminal of a battery is joined to one spring, and the line wire, *L*, connects the other

spring with a Bell receiver at the distant station. The circuit is then complete, and a steady current goes through both instruments. But when one speaks into ***M***, the air waves will vibrate the disk, causing the pressure of the knob against *C* to increase and diminish, and making the resistance of the loose contact to vary. In this way, an undulating current is transmitted which sets up vibrations in the disk of the receiver.

Fig. 319.

c. But instead of sending the battery current directly to the receiver, it is sent through the primary of an induction coil. The induced current, of higher E.M.F. (§ 221, *e*), traverses the line and vibrates the disk of the receiver more effectively.

In the "long-distance" transmitter, the carbon is granular instead of hard, so that the air-wave pressure acts on a large number of contact surfaces, causing greater variations in resistance. A more powerful battery, and a return wire instead of the earth circuit, also improve the action.

d. A small magneto-machine, whose armature is turned by a crank, is placed at each station in order to call the attention of the attendant at the other. The current of this little hand dynamo rings a bell both at the sending and receiving station. Finally, Fig. 319 shows the outfit for each station. The induction coil is in the same case with the transmitter.

e. There are nine events which follow one another in regular succession in talking through the telephone. The ***first*** is the production of air waves in the transmitter. The ***last*** is the reproduction of similar air waves in the receiver. Can you name the nine in their order?

XII. ELECTRIC HEAT AND LIGHT.

HEAT PRODUCED BY CURRENT.

226. **Electric Heat.** — *a.* One who handles the wires of electric circuits often finds that they are warmed by the currents which they carry. In fact, heat is always produced in electric circuits, and when the current is strong and the resistance in the circuit large, the temperature may be very high. This may be shown as follows:

Experiment 159. — Stretch an iron wire, No. 30, between two supports, (*pp′*, Fig. 320), 10 to 15 inches apart, and connect one end firmly with one terminal of a battery consisting of several cells *in series*. Place the other terminal, *s*, upon the wire at the other end, and gradually slide it toward *p*. Watch for evidence of heat. Estimate the length of the wire, which can be made red hot. Try a copper wire, No. 30, the resistance of which is less than that of the iron, and also a German silver wire, No. 30, whose resistance is greater. Estimate the length which can be heated to about the same temperature in each case, to see if you can detect any relation between the heat and the resistance of the wire.

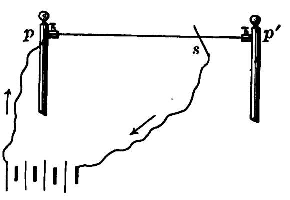

Fig. 320.

b. By precise experiment Joule discovered the following laws:

1. *The quantity of heat produced in one second by a current of given strength is proportional to the resistance of the conductor.*

2. *The quantity of heat in one second varies as the square of the strength of current.*

3. *The quantity of heat in one second, by a current of* 1 *ampere through a resistance of* 1 *ohm, is* .24 *calorie.* A calorie

is the quantity of heat which will raise the temperature of 1 g. of water 1° C (§ 92, *b*).

Hence the quantity of heat produced by any current, through any resistance, in any time, will be:

$$\text{Calories} = .24 \times \text{amperes}^2 \times \text{ohms}.$$

To illustrate: A current of 20 amperes, if passed through a wire whose resistance is 25 ohms for 30 seconds, will develop heat $.24 \times 400 \times 25 = 2400$ calories.

Examples. — 1. If the wire, which carries the current just described, is immersed in 800 g. of water at 15° C., what temperature would the water reach at the end of the 30 seconds if no heat escaped?

2. If the same quantity of heat is applied to 200 g. of water, or ¼ as much as before, how would the *rise of temperature* compare in the two cases?

3. Suppose the same quantity of heat to be used to heat 200 g. of copper, whose specific heat (§ 94, *a*, *d*) is .095, how would the rise of temperature compare with that of the 200 g. of water?

c. The *rise of temperature* depends not only on the quantity of heat used, but on the nature of the body in which it is developed. If the foregoing problems have been solved, their solutions illustrate this law: *The rise of temperature, due to a given quantity of heat, varies inversely as the mass and the specific heat of the substance.* For example: 100 calories would heat a thin copper wire to a higher temperature than a thick copper wire of the same length, because there is less copper to be heated. It would heat an iron wire of the same mass as the copper wire to a higher temperature, because the specific heat of iron is less. Hence the *rise of temperature* is represented as follows:

$$\text{Centigrade degrees} = \frac{\text{calories}}{\text{sp. heat} \times \text{grams}}.$$

d. Electric heat is now used for welding, brazing, and tempering metals. A current of great strength, but small E.M.F., is employed for these purposes. Such a current generates heat

enough in overcoming the resistance at the contact of the surfaces of two pieces of metal to quickly raise the temperature so high as to soften or even melt them. Thus the ends of two rails of a railway track are welded by softening them while in contact, and then pushing them together by heavy pressure. The current is usually obtained by transforming (§ 221, *a, e, g, h*) a strong alternating current of, say, 300 volts to 2 volts or less.

e. Electric heat has been used to some extent in getting metals from their ores; the manufacture of aluminum bronze by the "Cowles process" is the best example. The crushed ore, mixed with copper (or some other metal) and fine charcoal, is placed in an appropriate box. Insulated wires lead a heavy current into the box. Intense heat is developed by the resistance of the mixture, the ore is decomposed by it, and the aluminum combines with the copper to form aluminum bronze.

f. An *electric heater* is a device for heating by electricity. It consists usually of coils of wire, with high resistance, through which heavy currents may be passed. The coils may be placed inside of metallic boxes which will radiate the heat produced, or they may be immersed directly in a liquid which is to be heated. Thus a coil in a suitable box with an iron top is an *electric stove,* which can be used for culinary purposes. Or a kettle of the usual form, having a coil fixed inside upon the bottom, is an *electric teakettle.* Electric cars are often warmed by electric heaters.

227. **Electric Light.** — *a.* We have learned that radiant heat and light are essentially the same kind of energy (§ 138, *a*). Whenever any refractory solid is heated to sufficiently high temperature, it emits light, and if the heat is due to a current, the light is called *electric light.* On these facts are founded the practical methods of electric lighting. Electric lamps are of two kinds, — *incandescent* or *glow lamps,* and *arc lamps.*

b. In the incandescent lamp, the light is emitted by a thin,

infusible conductor of high resistance, which is heated nearly white hot by a current. Practically, the only substance used for this purpose is carbon. Other substances, metals for example, are liable to melt. On the other hand, carbon is very combustible in air, but this objection to its use is overcome by inclosing it in a vacuum.

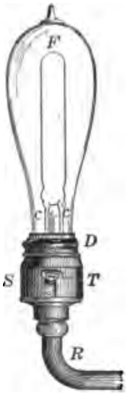

Fig. 321.

c. Fig. 321 represents an Edison glow lamp. A filament of bamboo, little thicker than a horsehair, is carbonized in the form of a loop, *F*. Its ends are fixed to two insulated platinum wires, *c*, *c*. These pass through a stopper which closes the end of the lamp at *D*. When this lamp is screwed upon a socket, *S*, borne by the fixture, *R*, the wires, *c*, *c* are brought in connection with the line by contact with two insulated brass plates in the socket, in which the line terminates. A turn-off, *T*, enables one to light or extinguish the lamp by closing or opening the circuit.

d. Incandescent lamps are usually connected in parallel, as shown in Fig. 322. All the lamps take current directly from one of the line wires, *MC′*, and return it to the other, *CL*. Each lamp requires the same current as every other. For example,

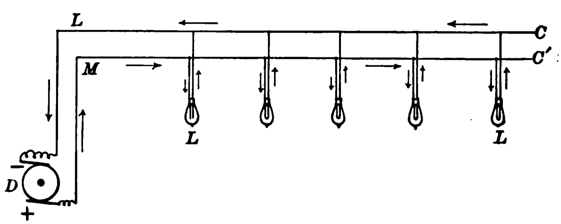

Fig. 322.

the Edison lamp of 16 candle-power requires a current of about .5 ampere at 110 volts. So the dynamo, *D*, must yield a current of *constant potential* — 110 volts — but of *varying*

strength, according to the number of lamps, .5 ampere for one, 5 amperes for ten, and so on. In this way the lamps are independent of one another; any number may be lighted or extinguished without affecting others.

e. Those who use electric light are sometimes charged a fixed rental *per lamp*, and sometimes a fixed price *per watt-hour*. By watt-hour is meant a current of 1 ampere at 1 volt for 1 hour.

An Edison lamp which requires .5 ampere at 110 volts, takes $110 \times .5$, or 55, watts. To light this lamp from 6 o'clock P.M. until 10 P.M., the electric light company must actually deliver 55 watts continuously for 4 hours, and the consumer will be charged for 55×4, or 220, watt-hours. *Watt-meters* are instruments by which electrical energy is measured in watts.

228. **Arc Lamps.** — *a.* Arc lamps have grown out of a discovery made by Humphry Davy, in 1800, which may be illustrated by the following experiment:

Experiment 160. — Connect the terminals of a battery, of several cells in series, with the ends of two carbon "pencils," or pointed carbon rods, (C, C', Fig. 323). First bring the points together, and then separate them a very little distance, perhaps equal to the thickness of a sheet of tissue paper, but greater if the E.M.F. of the current is high. You should observe what Davy saw, — a brilliant light emitted by the white-hot tips of the carbons. Before actual contact, no sign of a current can be detected.

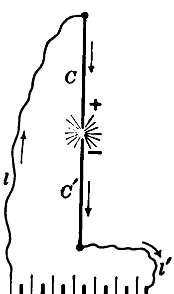

Fig. 323.

b. The *explanation* of these facts is as follows: The E.M.F. of the current is too low to throw a current across an air space of even .0001 inch between the points, but by actual contact a current is established. The resistance at the points is very great, and they become hot. At the moment of separation, the intense heat volatilizes a little carbon; the vapor is a better conductor than air, so that the current continues to pass through the vapor which it supplies, unless the gap becomes too wide.

The space between the glowing points is called the *voltaic* or *electric arc.* It is the seat of the intensest heat, but the tips of the carbons emit the chief part of the light, because matter is a better *radiator* in solid than in gaseous form.

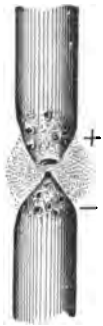

Fig. 324.

c. By means of a convex lens, a magnified image of the electric arc (Fig. 324) may be thrown on a screen, and a study of the image reveals some interesting facts:

The + carbon is more intensely bright than the – carbon. The end of the + carbon becomes concave; that of the – becomes pointed. A less brilliant purple aureole of incandescent vapor surrounds the tips and fills the space between.

Both carbons waste away, but the + nearly twice as fast as the –. Thus the length of the arc increases, and unless the tips are carried by some means nearer together again, the light is suddenly extinguished.

d. In almost all practical forms of arc lamp, the lower carbon is fixed and the upper one is held by a lever or clutch, which lets it fall gradually by its own weight as the gap widens. The clutch is operated by an electro-magnet, around which the current goes on its way to the carbon. As the gap widens, the current weakens; the magnet loses strength and lets the carbon down. Fig. 325 represents a common form of the arc lamp. The regulator is encased in the upper part, *R.* The course of the current may be traced by means of the arrows.

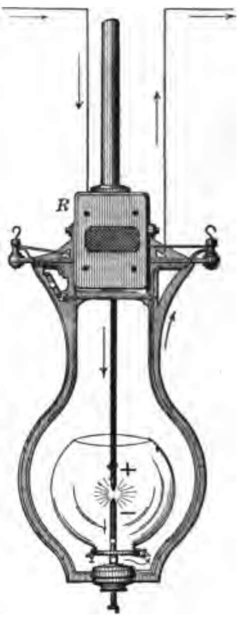

Fig. 325.

e. Arc lamps are usually connected in series, as shown in Fig. 326. Each lamp takes the current that has passed through all those that precede it on the circuit.

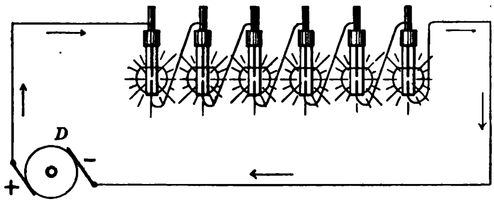

Fig. 326.

Each lamp requires a current of about 8 or 10 amperes at 45 or 50 volts. So the dynamo, *D*, must yield a current of *constant strength*, but of *varying potential*, according to the number of lamps. As many as 60 or even 80 lamps are sometimes lighted by one machine. Suppose each lamp to take 450 watts (§ 221, *i*) at 45 volts, then the machine must be able to give a current having a constant strength of 10 amperes, and a voltage ranging from 45, when only one lamp is lighted, up to 3600 volts when the 80 are turned on.

CURRENT PRODUCED BY HEAT.

229. **Thermoelectric Currents.** — *a.* Heat may be transformed directly into electric current. To produce a thermoelectric current, proceed as follows:

Experiment 161. — To the ends of a heavy German silver wire, *L* (Fig. 327), about six inches long, fasten two copper wires, *C*, *C*, by twisting them together firmly with pliers. Join *C*, *C* to a low resistance galvanometer, *G*. Warm the junction, *a*, of the two metals by hot water or the hot air above a lamp flame, and watch the galvanometer. Note the direction of its swing. Immerse *a* in ice water, and note the swing of the needle. Thus you observe the opposite directions of currents due to heat and cold.

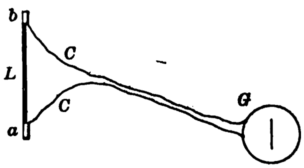

Fig. 327.

Then warm the junction *b*. You should observe the opposite directions of the currents due to heat when applied to the two junctions of the metals.

b. Two bars of different metals joined at one extremity are called a *thermoelectric pair.* If the circuit be closed by joining the other extremities of the pair, a current will be set up whenever the two junctions differ in temperature. The E.M.F. of the current with a single pair depends on the kinds of metal and the difference of temperature between the two junctions, but it is always very low. For example: If the junction of a *German-silver-copper* pair is 1° C. warmer than the rest of the circuit, the E.M.F. of the current is 15.55 microvolts (*micro* = one millionth).

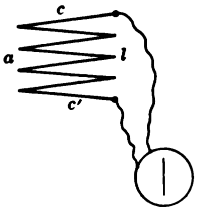

Fig. 328.

c. The E.M.F. of a thermoelectric current may be increased by joining pairs in series (Fig. 328). Several thermoelectric pairs in series are called a *thermoelectric pile.* Bismuth and antimony are used in small piles, because of their greater difference of potential, but large piles, or thermoelectric batteries, contain cheaper and more durable metals.

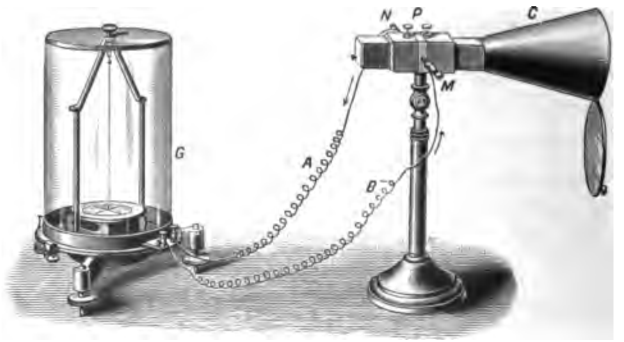

Fig. 329.

d. A thermopile of many pairs, with a sensitive galvanometer, constitutes an *electrical thermoscope,* which is invaluable as

an instrument to detect extremely small differences of temperature (Fig. 329). The pile, *P*, consists of, say, 40 pairs of small bismuth and antimony bars. The galvanometer, *G*, has a short coil (low resistance) and an astatic needle. The cone, *C*, is for the purpose of collecting radiant heat and concentrating it upon the face of the pile.

DISCHARGES IN VACUA.

230. **Electric Discharge through Gases and Vacua.** — *a.* When the difference of potential between two bodies is very great, a discharge takes place through the air. The appearances of this discharge, under different circumstances, are extremely varied and beautiful. *They depend on the density and the kind of gas* in which the discharge occurs.

b. The discharge may be studied by joining the secondary wires of an induction coil to brass rods which terminate in knobs inside an air-tight, oval-shaped vessel, which may be exhausted by an air pump. As the exhaustion proceeds, a *gradual* change goes on in the character of the discharge, but certain distinct features appear at certain stages, which we will describe.

Fig. 330.

1. At the ordinary density of the atmosphere the discharge appears as a brilliant, white, zigzag line of light between the knobs (Fig. 330). The resistance between the knobs converts the electric energy into heat, and the light is the glow of the intensely heated air along the path of the discharge. If the E.M.F. is 10,000 volts, the knobs may be separated about 1.4 cm. At this ratio, the E.M.F. necessary to produce a flash of chain lightning 1 mile long in air at ordinary density, has been computed to be equal to that of two hundred thousand 5000-volt dynamos in series.

2. As the exhaustion proceeds, the zigzag line changes to a diffuse glow (Fig. 331), red at the + and violet at the – knob, and the length of the discharge may be increased by separating the knobs. All this is due to diminution in density. The resistance of the air is diminished, hence the path may be longer, and the heat is less intense so that it no longer ignites the air to whiteness.

Fig. 331.

3. When the density is reduced to about .005, the glow begins to break up into cuplike layers of light, separated by dark spaces, with their convex surfaces toward the – knob (Fig. 332). As the exhaustion proceeds, these striæ grow more distinct and reach from knob to knob. The beauty of this *stratified discharge* is best seen in *Geissler tubes,* which are glass tubes with platinum wires sealed in at the ends, and containing various gases rarefied to about .0006. Each gas glows with a brilliant color of its own.

But if the exhaustion is continued, a dark space around the – knob extends further and further, driving the striæ before it until it reaches the + knob, and the whole distance is comparatively dark.

Fig. 332.

4. When the exhaustion has reached about .000001, an entirely new set of phenomena appears. The discharge no longer takes the shortest path between the knobs, or other electrodes, it goes in straight lines perpendicular to the surface of the – electrode, without any regard to the other. In the lower vacuum it is the gas in the tube that glows, but in this "high vacuum," not the contents of the tube, but the walls of the tube itself, are luminous. English glass glows with a beautiful violet color; German glass with green-

ish yellow; and if the discharge is thrown upon mineral matters within the tube, they also phosphoresce with rare beauty, each with its own peculiar color. A crystal of Iceland spar (Fig. 333) glows with brilliant yellow light.

Fig. 333.

The highly exhausted tubes for these results are known as *Crookes tubes*, the discharge in high vacua having been first studied by William Crookes about twenty-five years ago.

c. The residue of gas in these tubes is so different from ordinary air, that Crookes was constrained to consider it a fourth form of matter, which he termed *radiant matter*.

But the explanation seems to be this: The *kinetic theory of gases* teaches that molecules of gas are in ceaseless motion (33) *in straight lines*, changing direction only when they collide with one another. Of course, their paths between collisions become longer as the density becomes less, and when the density is reduced to .000001 or less, the molecules may fly the whole length of a tube with few collisions among themselves. On contact with the — electrode they are thrown from it in straight lines and strike the walls of the tube, where their energy is given up to the molecules of the glass. The remarkable fact is that *the seat of the electric energy, which drives the air molecules, is the — electrode.* The + electrode shows no such action.

d. The energy which goes from the — electrode of a high-vacuum tube constitutes what are called the *cathode rays*. These rays seem to consist of streams of electrified molecules of the residual gas, accompanied by disturbances in the ether. The streams of molecules were revealed by the experiments of

Crookes, and the ether disturbances were suggested by those of Hertz and Lenard. Thus in a Crookes shadow tube (Fig. 334), the anode, *A*, is an aluminum cross hinged upon a wire. When the cross is down, the rays have free course from the cathode, *C*, to the glass, and the large end of the tube glows brightly; but when the cross is erect, its dark shadow appears on the luminous glass. The molecular streams that produce the glow are unable to penetrate the compact metal. But Hertz, in 1891, showed that the aluminum, when thin, does transmit something, and Lenard succeeded in letting that something out through a very thin aluminum window into the air outside. These transmitted rays, according to Lenard, are disturbances in the ether.

Fig. 334.

e. In 1895 Roentgen (Rent'ken) discovered that the field outside of an excited high-vacuum tube is filled with invisible rays. He surrounded the tube with a shield of black paper. At a distance he placed a paper screen covered with barium platino-cyanide, and, in a completely darkened room, he saw this screen lighted with brilliant fluorescence. Not knowing what produced this effect, he designated the unknown cause the *X-rays*.

The most striking characteristic of the X-rays is *their power to penetrate opaque bodies.* They pass freely through blocks of wood, thick books, and plates of ebonite. In fact, all bodies seem to be transparent, but in different degrees, to these rays. Metals are more opaque than other substances, and bone is more opaque than flesh.

Two most interesting effects of the X-rays are the *lighting up of many fluorescent substances*, and the *chemical action on photographic plates.* Roentgen placed his hand between the

tube and a fluorescent screen and saw a shadow of the bones clearly defined on the paper. The X-rays passed freely through the flesh to illuminate the screen, but were intercepted by the bones. He substituted a photographic plate for the screen and obtained a picture of the skeleton of the hand, the more transparent flesh being faintly shown.

Among other properties which distinguish these rays, Roentgen found the following: They cannot be reflected, refracted, dispersed, nor polarized like radiant heat and light, nor can they be deflected by a magnet, like the "radiant matter" of Crookes, or the cathode rays.

The *nature* of the X-rays is still unknown, and even their origin is in doubt. But recent experiments seem to show that they are produced by the cathode rays striking the walls of the vacuum tube, or any other surface in their pathway. The bombarded surface, rather than the cathode, seems to be the source of the X-rays in the field outside the tube. And as to their nature, nothing is known beyond doubt. The belief is at present growing stronger that they are ordinary transverse ether waves whose wave lengths are less than those of the most ultraviolet light.

RADIANT ELECTRICITY.

231. **Radiant Electricity or Light.** — *a.* We have seen that radiant heat and light originate in the molecular vibrations of their source, and are transmitted by waves in the ether. Recent investigations have shown that electric vibrations and waves exist also, and seem to have proved that light is the result of these electric undulations.

b. The *electric spark* is not a single rush of energy, but *an oscillation.* This is a fact established by many experiments. It is also in accord with theory. For if the ether is strained by an electric charge, it should, like any other elastic substance,

vibrate when released from the stress; that is, when the discharge takes place. So in the discharge of a Leyden jar the electric energy surges back and forth many times between the knobs. By a succession of sparks, as in the discharges of an induction coil, these surgings are kept up, as the vibrations of a tuning fork are made to continue by periodic blows upon the prongs. But if electric vibrations occur, electric waves should exist also; for the perfectly elastic ether must transmit the electrical disturbance as inevitably as air transmits the simple harmonic motion of a tuning fork.

The existence of electric waves is not an inference from the oscillatory nature of an electric spark alone; it is attested by many direct experiments. The first of these were made by Hertz, in 1888.

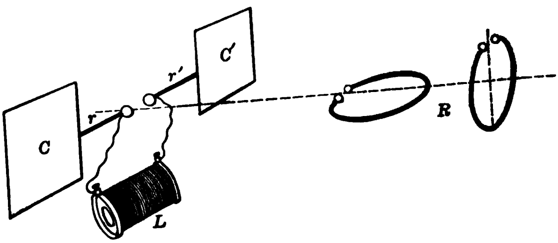

Fig. 335.

c. To *produce the electric vibration*, Hertz used an induction coil, *L* (Fig. 335), in connection with two metallic rods, *r*, *r'*, each ending in a small ball at one end, and carrying a large sphere or plate, *C*, *C'*, at the other end. This apparatus is called the *oscillator*. When in action, the coil charges the plates, and they discharge across the air gap between the knobs. A rapid succession of sparks keeps up the oscillations at the rate of many millions per second.

To *detect the electric waves* he used an open wire ring, *R* (Fig. 335), terminating in small balls whose distance apart could be varied at will. This is called the *resonator*. In

action, when the resonator is set in front of the knobs of the oscillator and in either of the two positions shown, sparks pass between its balls.

d. The *existence of electric waves was proved* by showing that the electric energy which passed from the oscillator to the resonator could be reflected, refracted, dispersed, polarized — in fact, that it had all the properties of waves in an elastic medium. For example, reflection was shown by a sheet of zinc bent into the form of a parabolic reflector, *R* (Fig. 336), with the oscillator, *O*, placed along its focal line. The resonator would emit sparks when held *directly in front of the reflector*, but not otherwise, showing the reflection of a parallel beam, as light would be reflected if a luminous body were at the focus instead of the oscillator. A plane sheet of metal, standing obliquely at a distance in front of *R*, threw the beam back, and the resonator showed that the electric waves made angles of incidence and reflection equal (§ 120, *c;* § 146).

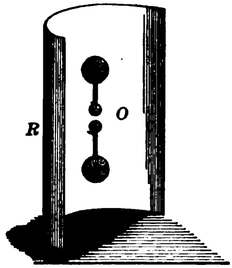

Fig. 336.

e. The interference of electric waves was shown as follows: The metallic reflector was so placed that the waves were thrown back upon themselves. Then when the resonator was carried along the line from oscillator to reflector, the sparks became alternately strong and feeble. This showed that the direct and reflected waves formed nodes and segments, as do waves upon a cord whose end is shaken by a tuning fork (§ 133), or as two sounds produce beats (§ 136), or as two portions of light produce alternate light and darkness (§ 168). Hence the law of interference (§ 135, *d*) prevails in electric radiations. Hence, too, the wave-lengths of these radiations can be found, since the distance from one node to the next one is a half wave-length.

f. Electric waves emanate not only from a spark discharge, but from an alternating current also. So from the wire pathway of an alternating current, electro-magnetic waves ripple off through space. It is by such waves that induction currents are set up in neighboring conductors in closed circuits.

g. Long before the existence of these waves was proved, Clerk Maxwell (1865) demonstrated, mathematically, that *if such electric waves do exist, their velocity in space is the same as that of light.* He at once suggested the probability that *light waves are themselves electro-magnetic waves,* and this is Maxwell's *electro-magnetic theory of light.* Since the experiments of Hertz and others have proved that electric waves do exist, and that they are subject to the laws of interference, reflection, refraction, and other phenomena of light, this theory has been widely accepted. It seems to be almost demonstrated that luminous and electro-magnetic waves are the same in kind; in other words, that light and electric radiation are one.

APPENDIX.

I. THE GRAPHIC METHOD.

1. **Representing Quantities by Lines.** — *a.* Anything that can be measured may be represented to the eye by the length of a line. A line of any convenient length may be chosen to represent a unit or any other definite quantity. Then a line two, or three, or *n* times as long, will represent two, three, or *n* times that quantity.

b. Different quantities of the same kind may be represented on one line. To represent several different masses, for example, proceed as follows: Draw a straight horizontal line; letter it *OX*, with *O* at the left-hand end. Choose a certain length, say 1 cm., to represent a definite mass, say 2 pounds. Place dots at equal distances of 1 cm. along the line, measuring from *O*, and letter them *a*, *b*, *c*, and so on. Then the line *Oa* represents 2 pounds, *Ob* represents 4 pounds, *Oc* represents 6 pounds. Seven pounds are represented by the line from *O* to a point midway between *c* and *d*. Volumes, forces, time, — any quantities whatever, — may be represented in this way.

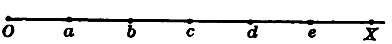

Fig. 337.

2. **Representing Related Quantities.** — *a.* One line may be constructed which will represent two related quantities at once. Take the case of a body in uniform motion. The distance it goes depends on the time it is kept in motion; hence distances and times are related quantities. The corresponding values of these can be found by experiment. Suppose that the observations in the following table have been made.

Times.	Distances.
1 sec.	10 ft.
2 "	20 "
3.5 "	35 "
5. "	50 "

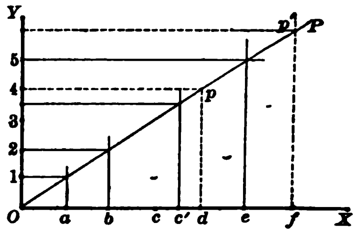

Fig. 338.

To construct a line that shall represent both the quantities at once, proceed as follows:

Draw two lines OX and OY (Fig. 338) at right angles, and place dots at equal distances from O on each. Now suppose the divisions on OX to represent *distances*, and let one division represent 10 feet. Also, suppose the divisions on OY to represent *times*, and let one division represent 1 second. Then the distances from O to a, b, c', e represent the distances 10, 20, 35, 50 feet, and the distances from O to 1, 2, 3.5, 5 represent the times 1, 2, 3.5, 5 seconds. From each of these points on OY draw light horizontal lines, and from each point on OX draw light vertical lines. Through the intersections of these lines draw the straight line OP. This is the line sought.

Every point in this line represents the corresponding values of the time and the distance of the moving body from the moment when it started from O. How far had it gone at the end of 4 seconds? Count 4 divisions on OY; draw a horizontal line to OP; it will reach that line at p, and a vertical line from p will reach d on OX. Now d is 4 divisions from O, and 4 divisions represent 40 feet. How long would it take this body to go 60 feet? Count 6 divisions from O on OX for the 60 feet; draw a vertical line to OP: it will reach p', and a horizontal line from p' will reach 6 on OY. Now 6 divisions on OY represent 6 seconds.

b. The two lines at right angles, OX and OY, are called *axes*. OX is the axis of *abscissas*; OY, the axis of *ordinates*; and O is called the *origin*. A line OP, which represents at every point the corresponding values of two related quantities, is called a *curve*, even when it is straight.

c. Much labor is saved if the paper on which curves are to be plotted is divided into equal squares, as shown in Fig. 339.

d. Mathematical work may be often saved by the use of a curve. For example, the value of any number of centimeters in inches, or of inches in centimeters, may be read directly from a curve without the trouble of computing it. The construction of this *centimeter-inch curve* shall be another and sufficient illustration of the graphic method.

The corresponding values of centimeters and inches, which are given in the table below, were obtained by Experiment 4, p. 16.

Let the origin O be at the left-hand lower corner of one of the larger squares on a sheet of curve paper (Fig. 339). Represent inches on OY, and centimeters on OX. Choose the following scales: let one division represent a half-inch, also let one division represent one centimeter. Number the inches on OY, and every fifth centimeter on OX. Now from 1 on OY count, on the horizontal line, 2.5 divisions for the 2.5 centimeters, and mark the point with a dot. From 2 on OY count 5.1 divisions horizontally for the 5.1 centimeters, and mark the point with a dot. In the same way place dots to mark the points which represent the inches and centimeters in each of the three other pairs of observations. Then draw a fine straight line from O through these dots. This line OP is the *curve* which shows the equivalent values of inches and centimeters.

Distance *ab*.			
1 inch	=	2.5	centimeters
2 "	=	5.1	"
$2\frac{1}{2}$ "	=	6.4	"
$3\frac{1}{2}$ "	=	8.8	"
5 "	=	12.7	"

How many centimeters are equal to 6 inches? $4\frac{1}{2}$ inches? $1\frac{1}{2}$ inches? How many inches are equal to 15 cm.? Convert 7 cm. into inches. Convert 7 inches into centimeters.

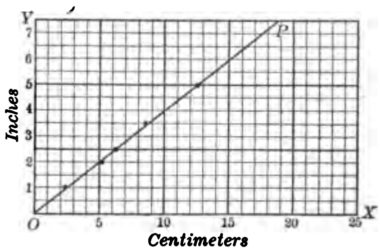

Fig. 339.

e. Since observations are not exact, the dots cannot be exactly in the right places, and a smooth straight line or curve will not pass exactly through them all. It should be always drawn so as to leave as many dots on one side of it as on the other. A dot very far away from the curve which includes the others shows that an error was probably made in that observation.

II. INTERPRETATION OF EXPERIMENTAL RESULTS.

1. Relations between Quantities.—The relations of quantities to each other are very generally expressed as proportions. Thus: The *weights* of bodies are *directly proportional* to their *masses*. The values of one quan-

tity may be directly or inversely proportional to those of the other on which they depend. They may be directly or inversely proportional to the squares of the others, or to the square roots. The object of much of the experimental work in physics is to discover these relations. They are the *principles* in physics, or the *laws of nature*.

How can these relations be discovered? Experiments must be made by which, in any case, the corresponding values of the related quantities are measured as accurately as possible. From these numerical values the relations may be discovered. How?

2. **By comparing their Products.** — *a*. To see how a relation can be expressed by products, take the case of articles of any one kind to be bought. The prices paid, A and B, will depend on the number purchased, C and D, so that we have $A : B :: C : D$. But we can change a proportion into an equation by writing the product of the extreme terms equal to the product of the mean terms. Thus, if 12 articles cost 4 dollars, 21 will cost 7 dollars, and if

$$4 : 7 :: 12 : 21, \text{ then } 4 \times 21 = 12 \times 7.$$
$$A : B :: C : D, \text{ then } A \times D = B \times C.$$

b. Conversely, if an equation consists of two products, we can change it into a proportion by writing the two factors of one product as the extreme terms, and the two factors of the other as the mean terms.

If $$A \times D = B \times C, \text{ then } A : B :: C : D.$$

c. Now suppose that we have two related quantities which we will call m and n, and suppose that we have found out by experiments that when two values of m have been multiplied each by the corresponding value of n, the two products are equal. We may write the equation and change it into a proportion. Thus:

$$m \times n = m' \times n'.$$
$$m : m' :: n' : n.$$

This proportion shows at a glance that the two values of m are inversely proportional to the two values of n. This illustrates the following general statement:

d. *If we multiply the corresponding values of two related quantities, and find that in several cases the products are equal, we infer that the quantities are inversely proportional to each other.*

3. **By comparing Quotients.** — *a*. If two quotients are equal, the two dividends are directly proportional to the two divisors.

If $$\tfrac{9}{3} = \tfrac{36}{12}, \text{ then } 9 : 36 :: 3 : 12.$$

If $$\frac{a}{b} = \frac{c}{d}, \text{ then } a : c :: b : d.$$

b. Now suppose that m and n stand for two related quantities, and we have found by dividing several values of m each by the corresponding value of n that the quotients are equal. We may write the equation, change it to a proportion, and infer the law which connects the two related quantities. Thus:

If $$\frac{m}{n}=\frac{m'}{n'},$$

then $$m \times n' = m' \times n,$$

and $$m : m' :: n : n'.$$

This proportion shows at a glance that the two values of m are directly proportional to the two values of n. This illustrates the following general statement:

c. If we divide the values of one of two related quantities, each by the corresponding value of the other, and find that the quotients are equal, we infer that the quantities are directly proportional to each other.

4. To discover the Law which connects Two Related Quantities. — *a.* We make an experiment involving the two quantities, and by repeated trials find several sets of corresponding values. Now one may vary directly as the other: To discover whether this law holds, compute their quotients. Or one may vary inversely as the other: To discover whether this law connects them, compute their products. If neither quotients nor products are equal, neither of these laws apply. Then try for the law of squares, or of square roots, by computing the squares or the square roots of the values of one of the quantities, and trying the quotients or the products as before.

b. This method of treating observations may be applied with advantage to the results in many of the experiments in this book. In Experiment 15, for example, it is proved that the two forces which act on a pivoted bar or lever do equal quantities of work. From this it is easy to obtain the *law* which connects the forces with their distances from the pivot or fulcrum. Thus the computations (p. 53) gave

$$F \times D = M \times d.$$
$$\therefore F : M :: d : D.$$

Since D and d stand for the lever arms of F and M (§ 25, *c*), this proportion shows that: *The two forces which balance each other on a lever are inversely proportional to their distances from the fulcrum.* This is the older form in which the *law of equilibrium for the lever* is stated.

c. Again: Experiment 16 proves that the two forces, the power, F, and the weight, M, which act on an inclined plane, do equal quantities of work. The computation shows that, in every case, $F \times L = M \times H$, and from these equal products we infer that: The two forces which work

against each other on an inclined plane are to each other inversely as the distances through which they move. These distances are the height, H, and the length, L, of the plane itself. Then if F be called the *power*, and M, the weight, as they are in the study of machines, we may state the law in this way: *The power and weight will balance each other on an inclined plane when the power is to the weight as the height of the plane is to its length.* This is the older form of the *law of equilibrium* for the inclined plane when the power is directed parallel to the length of the plane.

The translation of equations and proportions into laws is a most valuable exercise for the student.

III. TABLES.

1. EQUIVALENTS IN METRIC AND ENGLISH MEASURES.

Length.

.1 centimeter	= 1 millimeter	= 0.03937 inch.
100 centimeters	= 1 meter	= 39.3704 inches.
1000 meters	= 1 kilometer	= 39370.4 inches.

1 kilometer = 0.62137 mile.

Volume.

1 cubic centimeter	= 0.001 liter	= 0.06103 cubic inches.
1000 cubic centimeters	= 1. liter	= 1.0567 U.S. quarts.
1 liter	= 0.26417 U.S. gallons.	
1 liter	= 0.22008 imp. gallons.	
3.785 liters	= 1 U.S. gallon	= 231 cubic inches.
4.544 liters	= 1 imp. gallon	= 277.27 cubic inches.
29.57 cubic centimeters	= 1 U.S. fluid ounce	= $\frac{1}{16}$ U.S. pint.
28.4 cubic centimeters	= 1 imp. fluid ounce	= $\frac{1}{20}$ imp. pint.
1 U.S. fluid ounce	= 1.0412 imp. fluid ounces.	

Mass.

0.001 gram	= 1 milligram	= 0.01543 grain.
1000 milligrams	= 1 gram	= 15.4323 grains.
1000 grams	= 1 kilogram	= 2.2046 pounds (Avoirdupois).
28.349 grams	= 0.0284 kilogram	= 1 ounce (Avoirdupois).
31.103 grams	= 0.0311 kilogram	= 1 ounce (Troy).

2. RELATIVE DENSITIES OR SPECIFIC GRAVITIES (Approximate).

Aluminum	2.60	Paraffin	0.87–0.91
Brass, sheet	8.44	Platinum, wire	21.53
Copper, cast	8.30	Wax, white	0.96
Copper, sheet	8.88	Zinc, cast	7.00
German silver	8.43		
Glass, crown	2.52	Alcohol, absolute, 20° C.	0.789
Glass, plate	2.76	Alcohol, 90 %, 20° C.	0.818
Gold	19.32	Glycerine	1.26
Ice	0.917	Milk	1.032
Iron, cast	7.65	Turpentine	0.87
Iron, wrought	7.78	Water, 4° C.	1.0000
Lead, cast	11.36	Water, 20° C.	0.99827
Lead, sheet	11.40	Water, sea	1.027

3. BROWN AND SHARP WIRE GAUGE NUMBERS AND THEIR DIAMETERS IN MILLIMETERS.

No.	mm.	No.	mm.	No.	mm.
15	1.459	21	0.723	27	0.361
16	1.296	22	0.644	28	0.321
17	1.150	23	0.573	29	0.286
18	1.024	24	0.511	30	0.255
19	0.912	25	0.455	31	0.227
20	0.812	26	0.405	32	0.202

4. ELASTICITY OF SOLIDS.

Name of Substance.	Temp. C°.	Coefficient Kg. ÷ sq. mm.	Modulus $\frac{1}{\text{Kg.} \div \text{sq. mm.}}$	Tenacity Kg. per sq. mm.
Brass	15	0.0001007	9930	60
Copper	15	0.00008	12449	40
Iron, wire	15	0.000048	20869	63
Lead	15	0.000579	1727	2.15
Silver	15	0.000137	7284	29
Steel	15	0.000051	19549	83
Oak	15	0.001085	921	With the grain 5.66

IV. MISCELLANY.

1. **Solution for Soap Bubbles.** — Boil about 500 cc. of soft water, and when it is nearly cold measure out 400 cc., and add 10 g. of the best castile soap in fine shavings. Shake the mixture from time to time until the soap is dissolved. Set the solution aside for at least 24 hours. Pour off the clear liquid from the sediment, add 250 cc. of good glycerine, and mix the two thoroughly by shaking.

A test tube with a hole in the bottom is an excellent pipe.

2. **To clean Glass.** — Tubes and plates to be used for experiments on capillarity should be thoroughly clean. Oily matter is especially fatal to success. Let them be lifted up and down in strong sulphuric acid, then in clean water to remove the acid, afterwards in ammonia or caustic soda solution, and finally again in clean water. Handle them by grasping their upper ends or edges.

3. **To clean Mercury.** — Mercury may be freed from mechanical impurities by filtering it through a paper funnel having one or more pin holes pricked through it at the point. Mercury, in the laboratory, is likely to come into contact with lead and zinc, with which it readily combines. These metals may be removed by washing with moderately diluted nitric acid, then with pure water, and drying by contact with filter paper.

The best way to carry out the process of washing is as follows: A glass tube about an inch in diameter, and the longer the better, is provided at one end with a tightly fitting cork pierced by a short glass tube to which a short rubber tube with a pinchcock is attached. The tube is clamped upright, and three fourths filled with the fluid. The mercury is filtered through the pin holes of the filter in a glass funnel; it falls in minute streams through the fluid, collects at the bottom, and may be drained off. Instead of nitric acid a solution of 5 g. potassium bichromate and 5 cc. of strong sulphuric acid, per liter of water, can be used to advantage.

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NUMBERS REFER TO PAGES.

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Cooley, LeRoy C.
Physics.

NAME	DATE	NAME	DATE